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Published in:
Reviews of Modern Physics

DOI:
[10.1103/RevModPhys.87.1483](https://doi.org/10.1103/RevModPhys.87.1483)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2015

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Vos, K. K., Wilschut, H. W., & Timmermans, R. G. E. (2015). Symmetry violations in nuclear and neutron beta decay. *Reviews of Modern Physics*, 87(4), 1483-1516. <https://doi.org/10.1103/RevModPhys.87.1483>

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Symmetry violations in nuclear and neutron β decay

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(published 15 December 2015)

The role of β decay as a low-energy probe of physics beyond the standard model is reviewed. Traditional searches for deviations from the standard model structure of the weak interaction in β decay are discussed in light of constraints from the Large Hadron Collider and the neutrino mass. Limits on the violation of time-reversal symmetry in β decay are compared to the strong constraints from electric dipole moments. Novel searches for Lorentz symmetry breaking in the weak interaction in β decay are also included, where the unique sensitivity of β decay to test Lorentz invariance is discussed. In the conclusion a possible road map for future β -decay experiments is presented.

DOI: [10.1103/RevModPhys.87.1483](https://doi.org/10.1103/RevModPhys.87.1483)

PACS numbers: 11.30.Cp, 11.30.Er, 23.40.-s, 24.80.+y

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I. INTRODUCTION

The study of nuclear and neutron β decay has played a major role in uncovering the structure of the weak interaction, and therefore in the development of the electroweak sector of the standard model (SM) of particle physics. The intensity and the variety of β emitters, combined with the high precision with which β -decay parameters can be measured, ensured that β decay remained important in searches for new physics beyond the SM (BSM). Novel techniques of laser cooling and atom trapping (Sprouse and Orozco, 1997; Behr and Gwinner, 2009) made it possible to detect the momentum of the recoiling nucleus, allowing for further searches in unexplored observables that became available. New sources for slow neutrons enabled progress in the study of neutron β -decay observables (Abele, 2008; Nico, 2009; Dubbers and Schmidt, 2011). The motivation for these modern experiments is, on the one hand, to improve the accuracy of SM parameters, and, on the other hand, to search for physics BSM.

Searches for BSM physics in β decay look for deviations from the left-handed vector-axial-vector (“ $V - A$ ”) space-time structure of the weak interaction; see Severijns, Beck, and Naviliat-Cuncic (2006) and Holstein (2014) and references therein. High-precision β -decay experiments are sensitive to possible contributions of non-SM (or exotic) currents, in particular, right-handed vector, scalar, and tensor currents, that couple to hypothetical new, heavy particles. These exotic currents can also give additional violations of the discrete symmetries parity (P), charge conjugation (C), and time-reversal invariance (T).

Traditionally, β decay has been viewed as complementary to the direct searches for new, heavy particles at high-energy colliders. However, with the availability of meson factories the emphasis of searching for new physics in precise measurements of semileptonic decay parameters has shifted from β decay. New physics has also been severely constrained by the

emergence of the new field of neutrino oscillations and by the precise measurements of static observables such as the weak charges of quarks and electrons and the P - and T -odd electric dipole moments (EDMs) of particles, atoms, or molecules. Moreover, theoretical developments made it clear how various observables are interconnected, and therefore how the discovery potential of β -decay experiments compares to that of other fields.

Recently, another twist has been added to β decay as a promising precision laboratory to test the invariance of the weak interaction under Lorentz transformations, that is, boosts and rotations. The available evidence for the Lorentz invariance of the weak interaction is, in fact, surprisingly poor. The possibility to break Lorentz and the closely related CPT invariance (Greenberg, 2002) occurs in many proposals that attempt to unify the SM with general relativity, one of the central open issues in theoretical high-energy physics. During the last decade, the phenomenological consequences of such a breakdown of Lorentz symmetry have been charted (Colladay and Kostelecký, 1998), and recently such theoretical studies have been extended to β decay (Noordmans, Wilschut, and Timmermans, 2013b).

This review gives a broad overview of the searches for symmetry violations in nuclear and neutron β decay and discusses their significance compared to various other observables, both in precision measurements and in collider searches. In this way, it attempts to identify which β -decay studies are the most relevant to pursue. In Sec. II we first introduce the effective field theory (EFT) framework, which enables us to compare various experiments in a model-independent approach. We define the β -decay observables in Sec. III.

In Sec. IV we review the best bounds on exotic right-handed vector, scalar, and tensor couplings. We first address the most sensitive β -decay experiments, in which we also include limits from pion-decay experiments.

Second, we discuss how the neutrino mass and data from the Large Hadron Collider (LHC) experiments constrain BSM physics. We compare the bounds from these two sectors with the bounds from β -decay experiments. The violation of time-reversal invariance is discussed in Sec. V. In β decay, T violation manifests itself in nonzero imaginary parts of the couplings, which are probed by triple-correlation observables in β decay. We discuss how these bounds compare to those derived from the stringent upper limits on the values of EDMs.

In Sec. VI, we address the possibility that the weak interaction violates Lorentz symmetry, and, in particular, rotational invariance, in nuclear and neutron β decay. Such Lorentz violation (LV) would give rise to unique signals with no SM “background,” which, even when extremely small, could be experimentally detectable. Nuclear and neutron β decay offer a unique sensitivity to some Lorentz-violating parameters, especially in the gauge and neutrino sector, which we discuss separately.

We conclude with a road map for the opportunities in future β -decay studies, in light of the obtained and foreseen bounds from other frontiers.

II. FORMALISM

Nuclear and neutron β decay are semileptonic processes, mediated by the W gauge boson of the electroweak interaction. This interaction is described by a spontaneously broken $SU(2)_L \times U(1)_Y$ gauge symmetry. Under $SU(2)_L$ symmetry, left-handed leptons transform as a doublet, while right-handed particles are $SU(2)_L$ singlets. This is denoted by

$$L_A = (\nu_A, l_A)_L, \quad R_A = (l_A)_R, \quad (1)$$

where A is the flavor index and the left- and right-handed fields are

$$\psi_L \equiv \frac{1}{2}(1 - \gamma_5)\psi, \quad \psi_R \equiv \frac{1}{2}(1 + \gamma_5)\psi. \quad (2)$$

The W boson interacts only with left-handed fermions, which reflects the maximal violation of parity (P) symmetry in the weak interaction. In the minimal SM neutrinos are assumed to be massless, and right-handed neutrinos are absent. The role of the neutrino mass is discussed in Sec. IV.C.

The β^- (β^+) decay transition $d \rightarrow ue^- \bar{\nu}_e$ ($u \rightarrow de^+ \nu_e$) is, in the limit of infinite W -boson mass, described by the effective Lagrange density

$$\mathcal{L}_{\text{SM}} = \frac{G_F V_{ud}}{\sqrt{2}} \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \bar{u} \gamma^\mu (1 - \gamma_5) d + \text{H.c.}, \quad (3)$$

where G_F is the Fermi coupling constant, V_{ud} is the ud entry of the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix, and H.c. denotes the Hermitian conjugate. We work in natural units, $\hbar = c = 1$, and use $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$ and $\epsilon^{0123} = -\epsilon_{0123} = 1$.

At the nucleon level, all possible quark bilinears and their associated form factors need to be inserted (Weinberg, 1958), such that

$$\begin{aligned} \langle p | \bar{u} \gamma_\mu d | n \rangle &= \bar{p} \left[g_V(q^2) \gamma_\mu + \frac{g_M(q^2)}{M} \sigma_{\mu\nu} q^\nu + \frac{\tilde{g}_S(q^2)}{2M} q_\mu \right] n, \\ \langle p | \bar{u} \gamma_\mu \gamma_5 d | n \rangle &= \bar{p} \left[g_A(q^2) \gamma_\mu \gamma_5 + \frac{\tilde{g}_T(q^2)}{2M} \sigma_{\mu\nu} q^\nu \gamma_5 \right. \\ &\quad \left. + \frac{\tilde{g}_P(q^2)}{2M} q^\mu \gamma_5 \right] n, \end{aligned} \quad (4)$$

where $q = p_n - p_p$ is the momentum transfer and M is the nucleon mass. The vector form factor g_V and the axial-vector form factor g_A give the leading contributions to β decay, because the nuclei can be treated nonrelativistically. In the isospin limit, the induced form factor g_M , called weak magnetism, is given by $(\mu_p - \mu_n)/2$, i.e., the difference between the magnetic moments of the proton and the neutron. Given the current experimental precision, this form factor can be neglected, but future experiments might reach a level of precision for which weak magnetism has to be taken into account; see Sec. IV.D. In the isospin limit the induced scalar form factor \tilde{g}_S and tensor form factor \tilde{g}_T vanish (Weinberg, 1958), and we can neglect them at present. The induced pseudoscalar form factor \tilde{g}_P gets an additional suppression of

q/M , because of the $\bar{p}\gamma_5 n$ structure. We comment on pseudoscalar couplings in Sec. IV.A.5.

The leading-order SM expression for neutron decay is

$$\mathcal{L}_{\text{SM}} = \frac{G_F V_{ud}}{\sqrt{2}} g_V(q^2) \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \bar{p} \gamma^\mu \left(1 - \frac{|g_A(q^2)|}{g_V} \gamma_5 \right) n + \text{H.c.} \quad (5)$$

In the limit of $q^2 \rightarrow 0$, the vector charge is $g_V(0) = 1$, up to small corrections. This is dictated by the hypothesis of the conserved vector current (CVC). The axial-vector charge g_A is only partially conserved (PCAC). The best current value is derived from neutron β -decay experiments, $|g_A| = 1.2723(23)$ (Olive *et al.*, 2014).

In nuclear β decay one can exploit the properties of the parent and daughter nucleus to select particular parts of the interaction. Pure Fermi (F) transitions probe the vector currents (γ^μ), while pure Gamow-Teller (GT) transitions probe the axial-vector currents ($\gamma_5 \gamma^\mu$). Mixed transitions always require knowledge of the Fermi and Gamow-Teller transition matrix elements, $M_F \equiv \langle f | 1 | i \rangle$ and $M_{GT} \equiv \langle f | \vec{\sigma} | i \rangle$, respectively. The conditions for spin change (ΔJ) and parity change ($\pi_i \pi_f$) for Fermi and Gamow-Teller transitions are given in Table I. This table also lists for which aspect in SM and BSM research these transitions are used. We have defined the Fermi-Gamow-Teller mixing ratio

$$\rho \equiv g_A M_{GT} / g_V M_F, \quad (6)$$

and

$$\lambda \equiv |g_A| / g_V. \quad (7)$$

It is desirable to reduce the uncertainties of nuclear structure and select the simplest isotopes. For Fermi transitions the superallowed $0^+ \rightarrow 0^+$ transitions are of the most interest. For mixed transitions, mirror nuclei are preferred. For general mirror nuclei ρ has to be measured, while neutron decay ($J^\pi = 1/2^+ \rightarrow J^\pi = 1/2^+$, $|M_F|^2 = 1$, and $|M_{GT}|^2 = 3$) allows for the determination of the value of λ (Abele, 2008; Nico, 2009; Dubbers and Schmidt, 2011). An elaborate compilation of neutron-decay amplitudes is given in Ivanov, Pitschmann, and Troitskaya (2013).

When searching for physics BSM, nuclei serve as “micro-laboratories” that can be judiciously chosen to look for certain

manifestations of new physics. In this review, we address both the traditional searches for exotic couplings and the novel searches for Lorentz violation. In the latter, the possibility of angular-momentum violation needs to be considered, where the simplest of the forbidden decays, first-forbidden unique transitions, become relevant (Noordmans, Wilschut, and Timmermans, 2013a). Both fields search for BSM physics generated by an unknown fundamental theory at a high-energy scale. To study the effect of new physics at low energies, we work in an EFT approach. Within this framework the effects of new physics at low energies are described in a model-independent way with an effective Lagrangian of the form

$$\mathcal{L}^{(\text{eff})} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}. \quad (8)$$

The search for exotic couplings focuses on right-handed vector, scalar, and tensor couplings. These non-SM interactions can be included in the Lagrangian by adding higher-dimensional operators to \mathcal{L}_{BSM} . The effects of Lorentz violation can also be described in an EFT framework (Colladay and Kostelecký, 1998; Noordmans, Wilschut, and Timmermans, 2013b). We discuss both frameworks separately.

A. Exotic couplings

In EFT, deviations from the $V - A$ structure due to exotic couplings are generated by higher-dimensional operators, which are suppressed by the high-energy scale Λ . The effective Lagrangian is parametrized as

$$\mathcal{L}^{(\text{eff})} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^k} \mathcal{L}^{(4+k)}, \quad (9)$$

where

$$\mathcal{L}^{(4+k)} = \sum_i c_i \mathcal{O}_i^{(4+k)}, \quad (10)$$

and where c_i are dimensionless constants and $\mathcal{O}_i^{(4+k)}$ are dimension- $(4+k)$ operators. The SM only contains operators with mass dimension 3 or 4. For Lorentz-symmetric BSM physics, the lowest term we could add is $\mathcal{L}^{(5)}$. There is, however, only one dimension-5 operator, namely, the operator that generates Majorana neutrino masses (Weinberg, 1979). In

TABLE I. Classification of nuclear β decays and their characteristic use in the SM and in the search for BSM physics.

	F $\Delta J = 0$	GT $\Delta J = 0, \pm 1$ $\pi_i \pi_f = +1$	Mixed $\Delta J = 0$	First unique forbidden $\Delta J = \pm 2$ $\pi_i \pi_f = -1$	Section
SM parameter	V_{ud}	ρ	ρ, V_{ud}, λ		III
BSM	$A_{L,R}$	$\alpha_{L,R}$	$\alpha_{L,R}$		IV.A
T even					
BSM	\dots	$\text{Im} \alpha_L$	$\text{Im} A_L$ and $\text{Im} \alpha_L$		V
T odd			$\text{Im} \alpha_{LR}$		
LV	$\chi_{r,s}^{\mu\nu}$	$\chi_{i,a}^{\mu\nu}$		$\chi_{\mu\nu}$	VI
	\dots	\dots	a_{LV}	\dots	

searches for exotic couplings we assume the neutrino mass to be small, and therefore we neglect this operator. We focus only on $\mathcal{L}^{(6)}$, as even higher-dimensional terms are suppressed by additional powers of the large scale Λ .

The $\mathcal{O}_i^{(6)}$ that contribute to semileptonic charged decays are listed in [Cirigliano, Jenkins, and González-Alonso \(2010\)](#) and [Cirigliano, González-Alonso, and Graesser \(2013\)](#). At low energies these dimension-6 operators generate the original vector (C_V), axial-vector (C_A), scalar (C_S), pseudoscalar (C_P), and tensor (C_T) couplings of [Lee and Yang \(1956\)](#). At the quark level, the effective Lagrangian for β decay, with nonderivative four-fermion couplings, is¹

$$\mathcal{L}^{(\text{eff})} = \frac{4G_F V_{ud}}{\sqrt{2}} \sum_{e,\delta=L,R} \left\{ a_{e\delta} \bar{e} \gamma^\mu \nu_e^\epsilon \cdot \bar{u} \gamma_\mu d_\delta + A_{e\delta} \bar{e} \nu_e^\epsilon \cdot \bar{u} d_\delta + \alpha_\epsilon \bar{e} \frac{\sigma^{\mu\nu}}{\sqrt{2}} \nu_e^\epsilon \cdot \bar{u} \frac{\sigma_{\mu\nu}}{\sqrt{2}} d_\epsilon \right\}, \quad (11)$$

where we sum over the chirality (L, R) of the final states.

The coefficients represent

- $a_{e\delta}$: all possible V and A couplings.
- $A_{e\delta}$: exotic scalar and pseudoscalar couplings (where e denotes the chirality of the neutrino and δ the chirality of the d quark).
- α_ϵ : exotic tensor couplings (where ϵ denotes the chirality of both the neutrino and the d quark).

These coefficients are related to the couplings C_i and C'_i ($i = S, V, A, T, P$) of [Lee and Yang \(1956\)](#) by Eqs. (A3) and (A4) of Appendix A. In the SM all couplings except $a_{LL} = 1$ are zero. For tensor couplings, only α_L and α_R occur, since $\sigma_{\mu\nu} \gamma_5 = (i/2) \epsilon_{\mu\nu\alpha\beta} \sigma^{\alpha\beta}$. The constants $a_{e\delta}$, $A_{e\delta}$, and α_ϵ can be related to c_i , by matching their values at the low-energy scale with standard EFT techniques. The chiral structure of the coefficients is expressed by the first and second indices, which denote the chirality of the neutrino and the d quark, respectively. All couplings with first index R involve a right-handed neutrino. In the SM, right-handed neutrinos are absent, but they are present in many new-physics models. The role of the right-handed neutrino is discussed in Sec. IV.C. The new exotic couplings can be complex, representing the possibility of time-reversal (T) violation (Sec. V). The introduction of left-handed and right-handed couplings leads to parity violation when the coefficients differ. In the absence of right-handed couplings, parity violation is maximal.

To describe β decay of the nucleon we define the hadronic matrix elements ([Herczeg, 2001](#))

$$\langle p | \bar{u} \gamma_\mu d | n \rangle = g_V(q^2) \bar{p} \gamma_\mu n, \quad (12a)$$

$$\langle p | \bar{u} \gamma_\mu \gamma_5 d | n \rangle = g_A(q^2) \bar{p} \gamma_\mu \gamma_5 n, \quad (12b)$$

$$\langle p | \bar{u} d | n \rangle = g_S(q^2) \bar{p} n, \quad (12c)$$

$$\langle p | \bar{u} \gamma_5 d | n \rangle = g_P(q^2) \bar{p} \gamma_5 n, \quad (12d)$$

¹We follow [Herczeg \(2001\)](#), except for a factor $G_F V_{ud} / \sqrt{2}$ that we have extracted.

$$\langle p | \bar{u} \sigma_{\mu\nu} d | n \rangle = g_T(q^2) \bar{p} \sigma_{\mu\nu} n, \quad (12e)$$

modifying the effective Lagrangian in Eq. (11) accordingly. As before, the vector charge is $g_V \equiv g_V(0) = 1$. The other couplings g_A , g_S , g_P , and g_T can be calculated theoretically by using lattice QCD. Estimates for g_A on the lattice are currently not competitive with the experimental value $|g_A(0)| = 1.2723(23)$ determined from neutron β decay ([Olive et al., 2014](#)). The scalar, pseudoscalar, and tensor constants, g_S , g_P , and g_T , are determined theoretically. They are further discussed in Sec. IV.

Searches for exotic coupling also include searches for right-handed $V + A$ currents. Such currents are predicted for instance by left-right (LR) models, which add an $SU(2)_R$ gauge symmetry to the SM. This extends the SM with an additional gauge boson W_R , which mixes with the original SM W boson W_L . The weak eigenstates can be expressed in the mass eigenstates W_1 and W_2 as

$$W_L = W_1 \cos \xi + W_2 \sin \xi, \quad (13a)$$

$$W_R = e^{i\omega} (-W_1 \sin \xi + W_2 \cos \xi), \quad (13b)$$

where ξ is the mixing angle and ω is a CP -violating phase. The coupling of W_R to quarks and leptons introduces the right-handed coupling g_R and the right-handed CKM element V_{ud}^R , the equivalents of the SM parameters. The expressions for a_{LR} , a_{RL} , and a_{RR} in terms of these parameters are given in [Herczeg \(2001\)](#). A specific class of LR models are the symmetric LR models, in which P or C symmetry of the Lagrangian is imposed, which implies $g_L = g_R$. We focus on bounds for such models in Sec. IV.B.

B. Lorentz violation

The study of Lorentz violation is motivated by the possibility of spontaneous breaking of Lorentz invariance predicted by theories of quantum gravity ([Kostecký and Samuel, 1989](#); [Liberati and Maccione, 2009](#); [Liberati, 2013](#)). The natural energy scale for these theories of quantum gravity is the Planck scale, which lies 17 orders of magnitude higher than the electroweak scale. This precludes the direct detection of Planck-scale physics, but the effects of Lorentz violation at the Planck scale can become manifest at much lower energies, providing a “window on quantum gravity.” At low energy, Lorentz violation can be systematically described by the standard model extension (SME) ([Colladay and Kostecký, 1998](#)), by using an EFT approach. The SME contains all possible Lorentz-violating terms that obey the SM gauge symmetries, which include CPT -violating terms, since Lorentz violation allows for the breaking of CPT invariance. In fact, CPT violation can occur only if Lorentz symmetry is also broken ([Greenberg, 2002](#)).

Spontaneous Lorentz violation arises as Lorentz-tensor fields acquire a vacuum-expectation value (VEV), resulting in Lorentz-violating tensor coefficients in the SME Lagrangian. These coefficients can be understood as constant background tensor fields. Because of these tensor fields, the Lagrangian is no longer invariant under particle or active

Lorentz transformations, i.e., boosts or rotations of the particles, because the background fields do not transform under the Lorentz group (Colladay and Kostelecký, 1998). However, the low-energy theory remains invariant under observer Lorentz transformations, i.e., boosts or rotations of the observer's inertial frame. Because Lorentz symmetry is spontaneously broken, the underlying fundamental theory at the Planck scale remains Lorentz invariant, implying that important features such as energy-momentum conservation and microcausality are still valid. A possible experimental signature of Lorentz violation is a sidereal variation of observables, which arise as the laboratory moves through the Lorentz-violating background field when Earth rotates [other examples are given in, e.g., Mattingly (2005)].

Schematically, terms in \mathcal{L}_{BSM} in Eq. (8) can be written as (Colladay and Kostelecký, 1997)

$$\mathcal{L}_{\text{NP}} = \lambda^{(3)} \langle T \rangle \cdot \bar{\psi} \Gamma \psi + \frac{\lambda^{(4)}}{\Lambda} \langle T \rangle \cdot \bar{\psi} \Gamma (i\partial) \psi + \frac{\lambda^{(4+k)}}{\Lambda^k} \langle T \rangle \cdot \mathcal{O}^{(4+k)}, \quad (14)$$

where we summed over repeated indices and where $\lambda^{(i)}$ are dimensionless constants, $\langle T \rangle$ is the expectation value of tensor T , $\Gamma = 1, \gamma_5, \gamma_\mu, \gamma_\mu \gamma_5, \sigma_{\mu\nu}$ represents the gamma-matrix structure, and $\mathcal{O}^{(4+k)}$ are higher-dimensional operators. Furthermore, Λ represents the scale of the fundamental theory, which is naturally the Planck scale. The higher-dimensional operators are suppressed by powers of this high scale. The first two terms in Eq. (14) have mass dimensions 3 and 4, respectively. These terms are described in the original SME papers by Colladay and Kostelecký (1998) and are now referred to as the minimal standard model extension (mSME). For our present discussion we limit ourselves to the mSME, although higher-dimensional coefficients have also been described (Bolokhov and Pospelov, 2008; Kostelecký and Mewes, 2009, 2012, 2013).

From an EFT point of view, the introduced Lorentz-violating dimension-3 and dimension-4 operators are unnatural. Naively, one would expect the dimension-3 operators to scale linearly with the large scale Λ , while the coefficients of the dimension-4 operators should be of order unity. The experimental bounds on these dimension-3 and dimension-4 operators are much smaller, of course. This problem does not occur for higher-dimensional operators, which are naturally suppressed by the scale Λ . To evade these naturalness problems, the current limits on dimension-3 and dimension-4 coefficients require either large fine-tuning, or a symmetry that forbids these coefficients. However, even if dimension-3 and dimension-4 operators are forbidden at tree level, they will be induced by quantum corrections generated by higher-dimensional nonrenormalizable operators. These corrections scale quadratically with the cutoff scale, which might be as large as Λ . This can be circumvented by introducing new physics between the weak scale and the Planck scale. In that case, radiative corrections scale with a significantly lower cutoff scale (Mattingly, 2008). Such a scenario occurs in supersymmetry (SUSY) (Bolokhov, Groot Nibbelink, and Pospelov, 2005; Groot Nibbelink and Pospelov, 2005). SUSY restricts Lorentz-violating operators to dimension 5

and higher, and forbids those of dimensions 3 and 4. Dimension-3 and dimension-4 operators are generated by loop corrections if SUSY is broken. This would naturally lead to a suppression of m^2/Λ and m/Λ for dimension-3 and dimension-4 operators, respectively, where m is the SUSY-breaking scale (Bolokhov, Groot Nibbelink, and Pospelov, 2005; Groot Nibbelink and Pospelov, 2005). In the mSME, it is assumed that dimension-3 and dimension-4 operators are suppressed by some unspecified higher-scale mechanism, and the experimental constraints are studied without any assumptions on the nature of this suppression mechanism (Colladay and Kostelecký, 1998; Kostelecký and Russell, 2011).

The SME contains a large number of coefficients that parametrize possible Lorentz violation. We list the relevant coefficients for β decay, which are the lepton, Higgs, and gauge terms. The Lorentz-violating terms for leptons are (Colladay and Kostelecký, 1998)

$$\mathcal{L}_{\text{lepton}} = \bar{L}_A [i(c_L^{\text{LV}})_{\mu AB} \gamma^\mu D^\nu - (a_L^{\text{LV}})_{\mu AB} \gamma^\mu] L_B + \bar{R}_A [i(c_R^{\text{LV}})_{\mu AB} \gamma^\mu D^\nu - (a_R^{\text{LV}})_{\mu AB} \gamma^\mu] R_B, \quad (15)$$

where L denotes the $SU(2)_L$ doublet and R denotes the singlet, defined in Eq. (1). The subscripts A, B are flavor indices, and D_μ is the covariant derivative. This introduces the Lorentz-violating coefficients $a_{L,R}^{\text{LV}}$ and $c_{L,R}^{\text{LV}}$, which are CPT odd and CPT even, respectively. We introduced the superscript LV for these coefficients, in order not to confuse them with the coefficients in Eq. (11).

Before electroweak symmetry breaking, the Higgs and gauge sector are described by (Colladay and Kostelecký, 1998)

$$\begin{aligned} \mathcal{L}_{\text{Higgs+gauge}} &= [\frac{1}{2} k_{\phi\phi}^{\mu\nu} (D_\mu \phi)^\dagger D_\nu \phi + \text{H.c.}] + [ik_{\phi\phi}^{\mu\nu} \phi^\dagger D_\mu \phi + \text{H.c.}] \\ &\quad - \frac{1}{2} k_{\phi B}^{\mu\nu} \phi^\dagger \phi B_{\mu\nu} - \frac{1}{2} k_{\phi W}^{\mu\nu} \phi^\dagger W_{\mu\nu} \phi - \frac{1}{2} (k_G)_{\kappa\lambda\mu\nu} \text{Tr}(G^{\kappa\lambda} G^{\mu\nu}) \\ &\quad - \frac{1}{2} (k_W)_{\kappa\lambda\mu\nu} \text{Tr}(W^{\kappa\lambda} W^{\mu\nu}) - \frac{1}{4} (k_B)_{\kappa\lambda\mu\nu} B^{\kappa\lambda} B^{\mu\nu}, \end{aligned} \quad (16)$$

where $G^{\mu\nu}$, $W^{\mu\nu}$, and $B^{\mu\nu}$ are the $SU(3)_c$, $SU(2)_L$, and $U(1)_Y$ field-strength tensors, respectively, and ϕ is the Higgs doublet. The coefficient k_ϕ is CPT odd, and the only coefficient with dimension of mass. The other coefficients are CPT even and dimensionless. The coefficient $k_{\phi\phi}$ has symmetric real and antisymmetric imaginary components. The $k_{\phi W}$ and $k_{\phi B}$ coefficients are real and antisymmetric. The gauge couplings k_G , k_W , and k_B are real and have the symmetry properties of the Riemann tensor (Colladay and Kostelecký, 1998).

The SME parameters have been studied in a wide range of experiments (Kostelecký and Russell, 2011). The electromagnetic and gravity sectors have been studied extensively, whereas the number of searches in the weak interaction is rather low. This changed recently (Müller *et al.*, 2013; Noordmans, Wilschut, and Timmermans, 2013a, 2013b), and the search for Lorentz violation has been extended to weak decays, in particular, β decay. β decay places strong constraints on Lorentz-violating coefficients in the Higgs and gauge sector. In addition, β decay has a unique sensitivity to some coefficients in the neutrino sector (Díaz, Kostelecký, and Lehnert, 2013). We discuss these constraints in Sec. VI.

III. OBSERVABLES IN β DECAY

A. Correlation coefficients in β decay

In β decay, the correlations between different observables, such as the β momentum and the nuclear spin, can be measured. The amount of correlation is expressed in terms of correlation coefficients. These correlation coefficients depend on SM couplings and possible new V , A , S , P , and T interactions. Using the general effective Lagrangian in Eq. (11), we can write the decay-rate distribution for polarized nuclei as (Jackson, Treiman, and Wyld, 1957b)

$$\begin{aligned} \omega(\langle \vec{J} \rangle | E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu \\ = \frac{F(\pm Z, E_e)}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \\ \times \bar{\xi} \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right. \\ \left. + c \left[\frac{1}{3} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu} \right] \left[\frac{J(J+1) - 3\langle \vec{J} \cdot \vec{j} \rangle^2}{J(2J-1)} \right] \right. \\ \left. + \frac{\langle \vec{J} \rangle}{J} \cdot \left[A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \right\}, \quad (17) \end{aligned}$$

where $E_{e(\nu)}$, $\Omega_{e(\nu)}$, and $p_{e(\nu)}$ denote the total $\beta(\nu)$ energy, direction, and momentum, respectively, E_0 is the energy available to the electron and the neutrino, $\langle \vec{J} \rangle$ is the expectation value of the spin of the initial nuclear state, and \vec{j} is the unit vector in this direction; $F(\pm Z, E_e)$ is the Fermi function which modifies the phase space of the electron due to the Coulomb field of the nucleus. Also affecting the phase space is the Fierz-interference term, factorized with the coefficient b . This term is zero in the SM. We defined $\bar{\xi} \equiv G_F^2 V_{ud}^2 / 2\xi$, where ξ gives the strength of the interaction. The remaining terms describe the β -correlation coefficients: the β -neutrino asymmetry a , the P -odd “Wu parameter,” the β asymmetry A , the neutrino asymmetry B , and the triple-correlation coefficient D . The c coefficient vanishes for nonoriented nuclei and for nuclei with $J = 1/2$, such as the neutron. The c coefficient has not been taken into account in any experiment to date. However, in future experiments, which use laser beams to trap and cool samples, the expectation value $\langle (\vec{J} \cdot \vec{j})^2 \rangle$ may be affected, such that the c coefficient can play a role.

The decay rate integrated over the neutrino direction, but taking into account electron polarization, is (Jackson, Treiman, and Wyld, 1957b)

$$\begin{aligned} \omega(\langle \vec{J} \rangle, \vec{\sigma}_e | E_e, \Omega_e) dE_e d\Omega_e \\ = \frac{F(\pm Z, E_e)}{(2\pi)^4} p_e E_e (E_0 - E_e)^2 dE_e d\Omega_e \\ \times \bar{\xi} \left\{ 1 + b \frac{m_e}{E_e} + \frac{\vec{p}_e}{E_e} \cdot \left(A \frac{\langle \vec{J} \rangle}{J} + G \vec{\sigma}_e \right) \right. \\ \left. + \vec{\sigma}_e \cdot \left[N \frac{\langle \vec{J} \rangle}{J} + Q \frac{\vec{p}_e}{E_e + m} \left(\frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p}_e}{E_e} \right) + R \frac{\langle \vec{J} \rangle}{J} \times \frac{\vec{p}_e}{E_e} \right] \right\}, \quad (18) \end{aligned}$$

where $\vec{\sigma}_e$ is the spin vector of the β particle. This introduces the longitudinal β polarization G , the spin-correlation coefficients N and Q , and the triple-correlation coefficient R . The symmetry properties of the correlation coefficients are listed in Table II. The A , B , and G coefficients are associated with parity violation. Depending on the type of transition they can have SM values close to ± 1 , which is characteristic for maximal parity violation. The triple-correlation coefficients D and R are T odd and unmeasurably small in the SM (Herczeg and Khriplovich, 1997).

Integrating the decay rate over all kinematical variables gives the inverse lifetime,

$$\frac{1}{\tau} = \frac{m_e^5}{2\pi^3} f \bar{\xi} \left(1 + b \left\langle \frac{m_e}{E_e} \right\rangle \right), \quad (19)$$

where f contains the integration over the modified phase space and $\langle m_e/E_e \rangle$ is the average inverse energy in units of the electron mass.

In Appendix A we list the relevant correlation coefficients in terms of the couplings defined in Eq. (11) and the Fermi-Gamow-Teller matrix elements. The different correlation coefficients contain combinations of the complex V , A , S , P , and T couplings. Given the current experimental precision, we have neglected Coulomb corrections. These corrections mainly introduce additional imaginary couplings (except for the D and R coefficients) (Jackson, Treiman, and Wyld, 1957b).

We proceed by discussing how β -decay correlation experiments, combined with lifetime measurements, are used to obtain precise values for the SM V and A coupling strengths. In Sec. IV we discuss constraints on exotic couplings.

B. Standard model parameters in β decay

The correlation coefficients in Appendix A reduce to the SM expressions when putting the scalar and tensor couplings to zero, $a_{LL,LR,RR,RL} = 0$ and $\alpha_{L(R)} = 0$, and by using only $V - A$ couplings, $a_{LR,RR,RL} = 0$. The Fierz-interference coefficient b is zero in the SM. The lifetime in Eq. (19) can be derived from the ft value, using the measured half-life t instead of τ . In the SM,

TABLE II. Overview of symmetry properties under parity (P) transformations and time reversal (T) of the most relevant correlation coefficients in allowed β decay.

Coefficient	Correlation	P	T
a ($\beta\nu$ angular correlation)	$\vec{p}_e \cdot \vec{p}_\nu / E_e E_\nu$	Even	Even
b (Fierz-interference term)	m_e / E_e	Even	Even
A (β asymmetry)	$\vec{J} \cdot \vec{p}_e / E_e$	Odd	Even
B (ν asymmetry)	$\vec{J} \cdot \vec{p}_\nu / E_\nu$	Odd	Even
G (longitudinal polarization)	$\vec{\sigma}_e \cdot \vec{p}_e / E_e$	Odd	Even
N	$\vec{J} \cdot \vec{\sigma}_e$	Even	Even
Q	$\vec{\sigma}_e \cdot \vec{p}_e \vec{J} \cdot \vec{p}_e / E_e$	Even	Even
D (triple correlation)	$\vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu) / E_e E_\nu$	Even	Odd
R (triple correlation)	$\vec{\sigma}_e \cdot (\vec{J} \times \vec{p}_e) / E_e$	Odd	Odd

$$\frac{1}{ft} = \frac{m_e^5}{2\pi^3 \ln(2)} G_F^2 V_{ud}^2 g_V^2 |M_F|^2 (1 + |\rho|^2). \quad (20)$$

The SM value for G_F is obtained from muon decay (Webber *et al.*, 2011). It is important to note that if one considers non-SM contributions these may influence muon decay as well. In principle, g_A is calculable using lattice QCD, but as mentioned before, current lattice calculations are not as accurate as values derived from experiments and henceforth $\lambda = |g_A|/g_V$ is considered a free parameter. In general, M_F and M_{GT} need to be derived from nuclear model calculations. For superallowed Fermi transitions $\rho = 0$ and $M_F = \sqrt{2}$ in the isospin limit. Hardy and Towner (2009) analyzed all available superallowed Fermi transitions and derived a value for the ud CKM matrix element. Since the ft values of superallowed transitions should be equal, a large number of measurements could be combined, leading to the most precise value of $V_{ud} = 0.97425(22)$ (Hardy and Towner, 2009). In the analysis, details of the isotope-dependent nuclear-structure corrections on the matrix element M_F (e.g., isospin breaking) and the phase-space modifications are also considered. The superallowed transitions also give the best bound on the Fierz coefficient b in Eq. (19) by considering the energy dependence of the lifetime (Sec. IV.A.1).

The parameters λ and V_{ud} can also be determined from β -decay correlations in neutron decay and from the neutron lifetime (Abele, 2008; Nico, 2009; Dubbers and Schmidt, 2011; Wietfeldt and Greene, 2011). The best current values are $\lambda = 1.2723(23)$ (Olive *et al.*, 2014) and $V_{ud} = 0.9742(12)$ (Dubbers and Schmidt, 2011). The latter is more than 5 times less precise; see also Fig. 22 in Dubbers and Schmidt (2011). The strong Gamow-Teller dependence of neutron decay and the precision of the neutron-decay parameters is such that neutron decay also plays an important role in searches for tensor currents, as discussed in Sec. IV.A.3.

Another class of nuclei for which the nuclear structure is relatively well known are the mirror nuclei (Severijns *et al.*, 2008). Like neutron decay, mirror decays are mixed Fermi-Gamow-Teller transitions. Extraction of V_{ud} from lifetime measurements requires knowledge of the mixing parameter ρ , such that an additional measurement of at least one of the correlation coefficients is necessary. Naviliat-Cuncic and Severijns (2009) found $V_{ud} = 0.9719(17)$, using five available transitions. The important structure corrections to Eq. (20) for mirror nuclei have been evaluated (Severijns *et al.*, 2008), in analogy to the work of Hardy and Towner (2009) for superallowed Fermi decays. This new class of nuclei will broaden the spectrum of data and remove any possible bias in selecting only superallowed Fermi transitions in the determination of V_{ud} . Measurements with this motivation were undertaken. For example, Triambak *et al.* (2012), Broussard *et al.* (2014), and Shidling *et al.* (2014) measured the lifetime of two relevant mirror nuclei ^{19}Ne and ^{37}K . We will not review the status of this field here, but comment on their relevance in limiting left-handed tensor couplings via the Fierz-interference term in the next section. It demonstrates that the contribution of nuclear physics to high-precision SM data goes hand in hand with the searches for new physics in β decay.

IV. CONSTRAINTS ON EXOTIC COUPLINGS

β decay played an important role in establishing the $V - A$ structure of the SM, initially eliminating to a large extent the possible contributions of scalar and tensor interactions. Modern searches in nuclear β decay consider again scalar and tensor currents as possible very small deviations from the SM due to new physics (Severijns, Beck, and Naviliat-Cuncic, 2006; Severijns and Naviliat-Cuncic, 2011).

The searches in β decay are part of a much wider search in subatomic physics for new physics. Comparison between different searches has become possible in an EFT framework by using the effective Lagrangian in Eq. (11). At the quark level the relations between different observables are clean, but at the nucleon level they involve the nuclear form factors g_A, g_S, g_P , and g_T . Accurate values for these parameters are necessary in order to compare different limits. Recently, significant progress on the accuracy of both g_S and g_T has been reported. First results for g_P are also available. The most precise value for g_T is calculated with lattice QCD. Two recent results are from Green *et al.* (2012), $g_T = 1.038(16)$, and Bhattacharya *et al.* (2014), $g_T = 1.047(61)$.

The calculation method used in these works gives a much larger uncertainty for g_S . Estimates range from $g_S = 0.72(32)$ (Bhattacharya *et al.*, 2014) to $g_S = 1.08(32)$ (Green *et al.*, 2012). A value for g_S can also be derived using the CVC relation and lattice calculations (González-Alonso and Camalich, 2014),

$$g_S(0) = \frac{\delta M^{\text{QCD}}}{\delta m_q} = 1.02(11), \quad (21)$$

where both $\delta M^{\text{QCD}} = (M_n - M_p)^{\text{QCD}}$ (González-Alonso and Camalich, 2014) and $\delta m_q = m_d - m_u$ (Colangelo *et al.*, 2011) are obtained separately from lattice calculations. However, the determination of g_S with Eq. (21) might underestimate the error, because correlations between the numerator and denominator are neglected. Such errors could be avoided by calculating the ratio in Eq. (21) directly on the lattice. Further efforts to reduce the error for g_S directly on the lattice are being pursued (Bhattacharya *et al.*, 2012, 2014).

The pseudoscalar constant g_P can be calculated by using the PCAC relation. Combined with lattice QCD results (González-Alonso and Camalich, 2014) one finds

$$g_P(0) = \frac{\bar{M}_N}{\bar{m}_q} g_A = 349(9), \quad (22)$$

where $\bar{M} = (M_p + M_n)/2$ is the average nucleon mass and $\bar{m}_q = (m_u + m_d)/2 = 3.42(9)$ MeV is the average light-quark mass determined on the lattice (Colangelo *et al.*, 2011). According to Beringer *et al.* (2012), $\bar{m}_q = 3.5^{+0.7}_{-0.2}$ MeV, which gives a much larger error $g_P = 340^{+68}_{-19}$. Nevertheless, this shows that the pseudoscalar form factor is of the order of $\mathcal{O}(10^2)$. In β decay, pseudoscalar terms are generally neglected, because they occur only as higher-order recoil corrections. This suppresses pseudoscalar interactions compared to scalar and tensor interactions. The large value of g_P cancels this suppression to a large extent, and

β -decay experiments may be sensitive to pseudoscalar couplings after all. There are, however, already strong constraints on pseudoscalar couplings from pion decay, as discussed in Sec. IV.A.5.

In the remainder of this section we comment on searches for exotic couplings in β decay (Sec. IV.A), but consider only real couplings. We compare these results with constraints from the LHC experiments (Sec. IV.B) and due to the nonzero mass of the neutrino (Sec. IV.C). Bounds on imaginary couplings are discussed separately in Sec. V.

A. Constraints from β decay

In nuclear β decays, exotic couplings are mainly searched for in either pure Fermi or pure Gamow-Teller decays. Pure Fermi transitions depend on vector and possibly scalar couplings, while pure Gamow-Teller transitions depend on axial-vector and possibly tensor couplings. The use of mixed transitions is necessary when searching for interference terms. Preferred are isotopes with a relatively simple nuclear structure, e.g., mirror nuclei, or the neutron. We discuss the constraints from Fermi, Gamow-Teller, and mixed decays separately, focusing on the best current experimental data. We discuss the constraints on scalar and tensor couplings, while

assuming no additional vector or axial-vector interactions. For a fit of the data including these interactions we refer to [Severijns, Beck, and Naviliat-Cuncic \(2006\)](#), where also a review of the experimental techniques is given. We discuss $V + A$ couplings in Sec. IV.B.

Most β -correlation coefficients are measured by constructing asymmetry ratios. For example, the β asymmetry is measured from the quantity

$$A_{\text{measured}} = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}, \quad (23)$$

where $N(\uparrow)$ and $N(\downarrow)$ are the decay rates derived from measuring β particles in a particular detector while the polarization P of the nucleus changes sign. The arrows indicate the direction of polarization. The rates $N(\uparrow), N(\downarrow)$ correspond to the integration of Eq. (17) over all unobserved degrees of freedom, which removes the dependence on the neutrino direction. In the numerator only the P -odd term remains, while in the denominator the odd term drops out. However, the Fierz-interference term remains in the sum $N(\uparrow) + N(\downarrow)$, so that

$$A_{\text{measured}} = \frac{\int_{\Delta\Omega} \int_{E_{\min}}^{E_0} F(\pm Z, E_e) p_e (E_0 - E_e)^2 A |P| (p_e/E_e) \cos \theta_e dE_e d\Omega_e}{\int_{\Delta\Omega} \int_{E_{\min}}^{E_0} F(\pm Z, E_e) p_e (E_0 - E_e)^2 (1 + b/E_e) dE_e d\Omega_e} = \frac{A |P| \langle \beta_e \cos \theta_e \rangle}{1 + b \langle \frac{m_e}{E_e} \rangle}. \quad (24)$$

This implies that actually not the coefficient A is measured, but

$$\tilde{A} = \frac{A}{1 + b \langle m_e/E_e \rangle}. \quad (25)$$

The inverse average energy is approximated by

$$\left\langle \frac{m_e}{E_e} \right\rangle = \frac{\int_{E_{\min}}^{E_0} F(\pm Z, E_e) p_e (E_0 - E_e)^2 dE_e}{\int_{E_{\min}}^{E_0} F(\pm Z, E_e) p_e (E_0 - E_e)^2 E_e dE_e}, \quad (26)$$

which depends on the specific isotope and the experimental setup. In principle, the average energy could also depend on the angular distribution (θ_e). This makes it preferable that the analysis of $\langle m_e/E_e \rangle$ is done and published together with the observed correlation coefficients. At present, many of the values for $\langle m_e/E_e \rangle$ are derived by using the β -energy threshold E_{\min} ([Severijns, Beck, and Naviliat-Cuncic, 2006](#); [Pattie, Hickerson, and Young, 2013](#); [Wauters, García, and Hong, 2014](#)).

For the measured quantity \tilde{X} , $X = a, A, B, G$, etc., Eq. (25) applies. Except for B and N , the numerator of Eq. (25) depends only on the square of the coupling constants, while b has a linear dependence on left-handed couplings. In such cases one is most sensitive to b , and the measurement of \tilde{X} provides in the first place a measurement of the Fierz coefficient b . Therefore, the exact value of the $\langle m_e/E_e \rangle$ will

become increasingly important with increasing experimental precision.

1. Nuclear scalar searches

Throughout the discussion of limits on scalar and tensor couplings, we assume conventional left-handed vector couplings for the $V - A$ part, such that $a_{LL} = 1$, and $a_{LR, RL, RR} = 0$. These and the other couplings are defined in Eq. (11). The notation is chosen such that the difference between the left-handed and right-handed couplings of the neutrino is emphasized, i.e., for the scalar couplings $A_L = A_{LL} + A_{LR}$ (left-handed neutrino coupling) and $A_R = A_{RR} + A_{RL}$ (right-handed neutrino coupling). Further details on the notation and some relevant expressions can be found in Appendix A.

For pure Fermi transitions

$$\xi = 2|M_F|^2 g_V^2 \left\{ 1 + \left(\frac{g_S}{g_V} \right)^2 [A_L^2 + A_R^2] \right\}, \quad (27)$$

$$\xi b_F = \pm 4\gamma |M_F|^2 g_V g_S A_L, \quad (28)$$

from Eqs. (A9) and (A11), where b_F is the Fermi part of the Fierz coefficient b , the upper (lower) sign is for β^- (β^+) decays and $\gamma = \sqrt{1 - Z^2 \alpha^2}$, with Z the atomic number of the daughter nucleus and α the fine-structure constant. For the positron-emitting superallowed $0^+ \rightarrow 0^+$ Fermi decays

$$\frac{1}{ft_F} = \frac{m_e^5}{2\pi^3 \ln(2)} G_F^2 V_{ud}^2 g_V^2 |M_F|^2 \times \left\{ 1 + \left(\frac{g_S}{g_V} \right)^2 [A_L^2 + A_R^2] - 2\gamma \left\langle \frac{m_e}{E_e} \right\rangle \frac{g_S}{g_V} A_L \right\}. \quad (29)$$

Hardy and Towner (2009) obtained an average of all ft values, \overline{ft} , after the appropriate corrections for radiative and nuclear-structure effects. The current best value of V_{ud} is derived from \overline{ft} , assuming no exotic couplings. Allowing for scalar terms one can exploit (Hardy and Towner, 2005) the different values of $\langle m_e/E_e \rangle$ to put a stringent limit on the Fermi Fierz-interference coefficient (Hardy and Towner, 2009),

$$b_F = -0.0022(26) = -2 \frac{(g_S/g_V) A_L}{1 + (g_S^2/g_V^2)(A_L^2 + A_R^2)} \simeq -2 \frac{g_S}{g_V} A_L. \quad (30)$$

Although b_F is not sensitive to right-handed scalar currents, the value of \overline{ft} is sensitive to these. In fact, the bound on right-handed couplings is more than an order of magnitude larger than that of left-handed couplings, such that both contributions to the \overline{ft} values are of the same order, as can be seen in Eq. (29). Therefore, in searches for BSM physics one may not assume V_{ud} as given by the Particle Data Group (PDG) when such a search concerns also right-handed scalar terms. In the correlation coefficients, the value of V_{ud} mostly drops out, but in limits derived from measured lifetimes the actual value of V_{ud} is required.

Constraints on right-handed scalar couplings can be extracted from the β - ν -correlation coefficient a defined in Eq. (A10). We define $\delta_- = |a_{SM} - a_{exp}^-|$ as the lower bound and $\delta_+ = |a_{exp}^+ - a_{SM}|$ as the upper bound, where the experimental value, at 90% confidence level (C.L.), lies between a_{exp}^- and a_{exp}^+ . Limits from a then give

$$2 \left(\frac{g_S}{g_V} \right)^2 [A_L^2 + A_R^2] < \delta_-, \quad (31)$$

which gives a circular bound in the A_L, A_R plane. Thus, the bound on A_L and A_R would be the same,

$$\left| \frac{g_S}{g_V} A_{L(R)} \right| < \sqrt{\frac{\delta_-}{2}}. \quad (32)$$

In practice experiments normalize the correlation to the total number of counts, and the absolute normalization is not measured. This means that in fact \tilde{a} is measured, as discussed below Eq. (23). In this way the Fierz-interference term b enters. The bounds remain circular, but the bound on A_L changes to

$$\frac{-\delta_-}{2\gamma \langle m_e/E_e \rangle} < \frac{g_S}{g_V} A_L < \frac{\delta_+}{2\gamma \langle m_e/E_e \rangle} \quad (33)$$

for β^+ and with opposite signs for β^- .

Figure 1 shows the bounds from the best current experiments. The superallowed Fermi decays constrain only

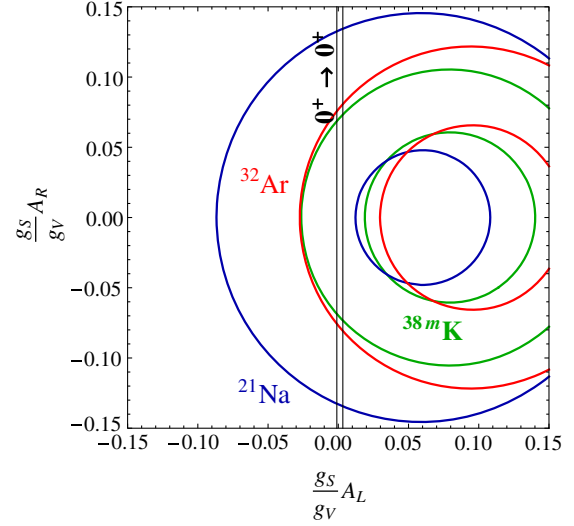


FIG. 1 (color online). Bounds on left- and right-handed scalar couplings (90% C.L.). The narrow $0^+ \rightarrow 0^+$ band is from superallowed Fermi transitions Eq. (30) (Hardy and Towner, 2009). The ring-shaped boundaries are derived from β - ν correlation measurements in ^{38m}K (Gorelov *et al.*, 2005) and ^{32}Ar (Adelberger *et al.*, 1999); cf. Eq. (33). Also the bound from the mirror nucleus ^{21}Na (Vetter *et al.*, 2008) is given, neglecting tensor contributions.

left-handed couplings and give a narrow vertical band (Hardy and Towner, 2009). The right-handed coupling A_R is constrained only by the β - ν correlations and depends on the square root of the experimental error δ_- . The most sensitive β - ν correlation measurements are from ^{38m}K (Gorelov *et al.*, 2005) and ^{32}Ar (Adelberger *et al.*, 1999). We also include the recent measurement of the mirror nucleus ^{21}Na (Vetter *et al.*, 2008), a mixed transition, where we have put tensor contributions to zero. In an earlier review this was erroneously shown with a bound as in Eq. (32) (Severijns and Naviliat-Cuncic, 2011). We show it because it is the first mixed transition available with such competitive precision. The best current bounds on real scalar couplings from pure Fermi decays are found by minimizing the χ^2 distribution of the b_F from Eq. (30) and the measurements of the β - ν correlation in ^{38m}K (Gorelov *et al.*, 2005) and ^{32}Ar (Adelberger *et al.*, 1999) (Table III). At 90% C.L.,

$$-0.1 \times 10^{-2} < \frac{g_S}{g_V} A_L < 0.3 \times 10^{-2}, \quad (34a)$$

$$-6 \times 10^{-2} < \frac{g_S}{g_V} A_R < 6 \times 10^{-2}. \quad (34b)$$

For A_L the bound comes from the strong limit on the Fierz-interference term. The limit on A_R is less strong. Improving the bound on right-handed scalar couplings substantially is a daunting task: exploiting the forward-backward symmetry in the β - ν correlation would require collecting 10^{14} events to reach a bound $< 10^{-3}$ on $g_S A_R$.

TABLE III. Experimental values used to construct Fig. 3. The values for $\langle m_e/E_e \rangle$ are mostly not calculated by the experimental groups and are derived with Eq. (26), except for the $0^+ \rightarrow 0^+$ decays, for which we use the value derived in Pattie, Hickerson, and Young (2013). Averages from the PDG are used only for the τ (Beringer *et al.*, 2012), since different measurements of \tilde{A} and \tilde{B} might also have a different energy dependence, which is not taken into account in the PDG averages. We have taken all experimental values for \tilde{A} used by the PDG.

Isotope	Parameter	Decay	$\langle m_e/E_e \rangle$	Value	Error	Reference
${}^6\text{He}$	\tilde{a}_{GT}	β^- , GT	0.286	-0.3308	0.003	He and McKellar (1993), Glück (1998)
${}^{14}\text{O}/{}^{10}\text{C}$	$P_{\text{F}}/P_{\text{GT}}$ (Eq. (38))	β^+	0.292	0.9996	0.0037	Carnoy <i>et al.</i> (1991)
${}^{26m}\text{Al}/{}^{30}\text{P}$	$P_{\text{F}}/P_{\text{GT}}$ (Eq. (38))	β^+	0.216	1.003	0.004	Wichers <i>et al.</i> (1987)
${}^{32}\text{Ar}$	\tilde{a}_{F}	β^+ , F	0.191	0.9989	0.0065	Adelberger <i>et al.</i> (1999)
${}^{38m}\text{K}$	\tilde{a}_{F}	β^+ , F	0.133	0.9981	0.0045	Gorelov <i>et al.</i> (2005)
${}^{60}\text{Co}$	\tilde{A}_{GT}	β^- , GT	0.704	-1.027	0.022	Wauters <i>et al.</i> (2010)
$0^+ \rightarrow 0^+$	b_{F}	β^+ , F	0.2560	-0.0022	0.0026	Hardy and Towner (2009)
n	τ [Eq. (A20)]	β^- , F/GT	0.655	880 s	0.9 s	Beringer <i>et al.</i> (2012)
n	\tilde{A}_n	β^- , F/GT	0.56	-0.11952	0.00110	Mendenhall <i>et al.</i> (2013)
n	\tilde{A}_n	β^- , F/GT	0.534	-0.11926	0.00050	Mund <i>et al.</i> (2013)
n	\tilde{A}_n	β^- , F/GT	0.582	-0.1160	0.0015	Liaud <i>et al.</i> (1997)
n	\tilde{A}_n	β^- , F/GT	0.558	-0.1135	0.0014	Erozolimskii <i>et al.</i> (1991), Yerozolimsky <i>et al.</i> (1997)
n	\tilde{A}_n	β^- , F/GT	0.551	-0.1146	0.0019	Bopp <i>et al.</i> (1986)
n	\tilde{B}_n	β^- , F/GT	0.594	0.9801	0.0046	Serebrov <i>et al.</i> (1998)
n	\tilde{B}_n	β^- , F/GT	0.63	0.9802	0.0050	Schumann <i>et al.</i> (2007)
n	\tilde{a}_n	β^- , F/GT	0.655	-0.1054	0.0055	Byrne <i>et al.</i> (2002)

2. Nuclear tensor searches

The nuclear Gamow-Teller matrix element M_{GT} can be evaluated only in the context of a nuclear model, because the spin of a nucleus is an observable, but the orbital angular momentum of a valence nucleon is not. For this reason M_{GT} cannot be evaluated sufficiently robustly to put a bound on the left-handed tensor couplings from ft values, as was done for the scalar coupling by using the superallowed Fermi decays. However, the Fierz-interference term will enter most observables via the normalization requirement discussed previously; cf. Eq. (25). The β -asymmetry coefficient A in Gamow-Teller decays is a good example of this, where

$$\tilde{A} = \frac{A_{\text{GT}}}{1 + b_{\text{GT}} \langle m_e/E_e \rangle} \approx \pm \lambda_{J'J} \left[-1 + 8 \frac{g_{\text{T}}^2}{g_{\text{A}}^2} \alpha_{\text{L}}^2 - 4 \frac{g_{\text{T}}}{|g_{\text{A}}|} \alpha_{\text{L}} \gamma \left\langle \frac{m_e}{E_e} \right\rangle \right], \quad (35)$$

from Eq. (A13). Thus in the absence of Coulomb corrections one finds that \tilde{A} becomes independent of α_{R} and therefore only limits on α_{L} can be obtained from \tilde{A} . Defining the experimental bounds of $\tilde{A} - A_{\text{SM}}$ as before gives

$$\frac{-\delta_-}{4\gamma \langle m_e/E_e \rangle} < \frac{g_{\text{T}}}{|g_{\text{A}}|} \alpha_{\text{L}} < \frac{\delta_+}{4\gamma \langle m_e/E_e \rangle}. \quad (36)$$

To obtain a bound on α_{R} one can exploit the β - ν correlation a . The result is similar to the result for a in Fermi decay. For β^- Gamow-Teller decay $a_{\text{SM}} = -1/3$ and the bounds are

$$\left| \frac{g_{\text{T}}}{g_{\text{A}}} \alpha_{\text{R}} \right| < \sqrt{\frac{3\delta_-}{8}}, \quad -\frac{3\delta_-}{4\gamma \langle m_e/E_e \rangle} < \frac{g_{\text{T}}}{|g_{\text{A}}|} \alpha_{\text{L}} < \frac{3\delta_+}{4\gamma \langle m_e/E_e \rangle}. \quad (37)$$

The limits on tensor interactions can be improved by combining scalar and tensor searches. In particular, the left-handed tensor couplings can be further constrained by using the measurements of the Fermi and Gamow-Teller-transition ratio of the longitudinal β polarization. These measurements were performed in the first place to study the manifest left-right symmetric model (Wichers *et al.*, 1987; Carnoy *et al.*, 1991); see also Sec. IV.B. The ratio of longitudinal polarizations (P , see Appendix A) of the emitted positrons was measured in the systems ${}^{26}\text{Al}^m/{}^{30}\text{P}$ (Wichers *et al.*, 1987) and ${}^{14}\text{O}/{}^{10}\text{C}$ (Carnoy *et al.*, 1991), where the first nucleus decays via a Fermi and the second a Gamow-Teller transition. The two transitions have nearly identical end-point energies, which eliminates systematic errors. The measured ratio is

$$\frac{P_{\text{F}}}{P_{\text{GT}}} \approx \frac{\tilde{G}_{\text{F}}}{\tilde{G}_{\text{GT}}} \approx 1 - 2 \left\langle \frac{m_e}{E_e} \right\rangle \left(\frac{g_{\text{S}}}{g_{\text{V}}} A_{\text{L}} + 2 \frac{g_{\text{T}}}{|g_{\text{A}}|} \alpha_{\text{L}} \right). \quad (38)$$

Combining these measurements with the bounds on b_{F} in Eq. (30) gives a more precise left-handed tensor bound, but it does not constrain right-handed couplings.

Figure 2 shows the best constraints on tensor couplings. We use the $P_{\text{F}}/P_{\text{GT}}$ values (Wichers *et al.*, 1987; Carnoy *et al.*, 1991), the β - ν correlation in ${}^6\text{He}$ (Johnson, Pleasonton, and Carlson, 1963; Glück, 1998), and the β asymmetry in ${}^{60}\text{Co}$ (Wauters *et al.*, 2010) (see Table III) to find the best bounds for nuclear searches, using χ^2 minimalization. For the $P_{\text{F}}/P_{\text{GT}}$ values we have included the limits on scalar couplings in

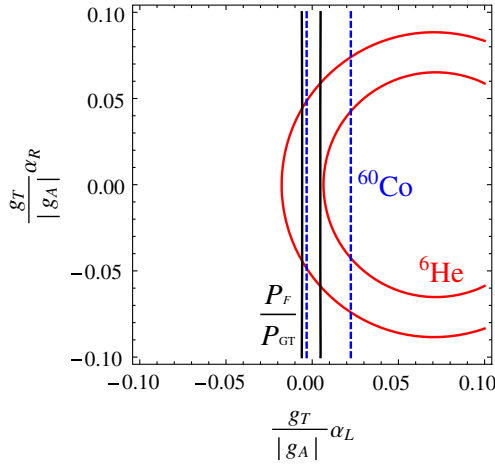


FIG. 2 (color online). Bounds on left- and right-handed tensor couplings (90% C.L.). The measurement of the β - ν correlation in ^6He (Johnson, Pleasonton, and Carlson, 1963; Glück, 1998) gives a ring-shaped boundary. The boundary of measurements of the β asymmetry in the pure Gamow-Teller decay of ^{60}Co (Wauters *et al.*, 2010) is given by dashed lines, the measurement only constrains left-handed couplings [Eq. (35)]. The strongest bounds on left-handed couplings are from measurements of the β -longitudinal polarization P_F/P_{GT} in Eq. (38) (Wichers *et al.*, 1987; Carnoy *et al.*, 1991), combined with the constraint on b_F .

Eq. (34). The combined fit for real tensor couplings gives, at 90% C.L.,

$$-0.3 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_L < 0.6 \times 10^{-2}, \quad (39a)$$

$$-6 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_R < 6 \times 10^{-2}. \quad (39b)$$

Reducing the limits will require increased statistics and experimental improvements (Sec. IV.D). Further constraints from β decay come from mixed decays which we discuss next.

3. Tensor constraints from neutron and mirror nuclei

Mirror transitions are mixed transitions and therefore sensitive to both scalar and tensor interactions. Mirror decays might be used to improve the bounds of pure Fermi and Gamow-Teller transitions discussed previously. At this point only the neutron can be considered. The prospects of using mirror nuclei are discussed at the end of this section. The neutron can serve as a laboratory for studying a range of fundamental interactions (Abele, 2008; Nico, 2009; Dubbers and Schmidt, 2011). In neutron β decay, the main focus lies on determining the SM parameters V_{ud} and $\lambda = g_A/g_V$. Non-SM values are included by allowing λ to be complex and/or by allowing for scalar (A_L, A_R) and/or tensor (α_L, α_R) interactions. We still consider only real couplings and defer to Secs. V.A.1 and V.A.2 for complex λ and scalar and tensor couplings, respectively. To clarify the role of possible left- and right-handed scalar and tensor contributions, we keep the simplifying assumptions that the V and A couplings are those of the SM. For neutron decay, with $M_{GT} = \sqrt{3}$ and $M_F = 1$, the ft value is given by

$$\begin{aligned} 1/ft_n = & \frac{m_e^5}{2\pi^3 \ln(2)} G_F^2 V_{ud}^2 g_V^2 \\ & \times \left\{ 1 + \left[\frac{g_S}{g_V} \right]^2 [A_L^2 + A_R^2] + 2\gamma \left\langle \frac{m_e}{E_e} \right\rangle \frac{g_S}{g_V} A_L \right. \\ & \left. + 3\lambda^2 \left(1 + \left[\frac{g_T}{g_A} \right]^2 [\alpha_L^2 + \alpha_R^2] - 4\gamma \left\langle \frac{m_e}{E_e} \right\rangle \frac{g_T}{|g_A|} \alpha_L \right) \right\}. \end{aligned} \quad (40)$$

The current value recommended for the lifetime is $\tau_n = 880.3(1.1)$ s (Olive *et al.*, 2014), which is nearly 6 s lower, but with the same error, as the recommended value of 2008. Of course, this affects the SM values for V_{ud} and λ , but cross-checks with other correlation coefficients are possible, allowing for consistency of the SM parameters (Wietfeldt and Greene, 2011). Including scalar and tensor contributions increases the number of degrees of freedom and such cross-checks are no longer possible. The observable ft_n is most sensitive to α_L , because of the partial Gamow-Teller nature of neutron decay. One can combine various correlation coefficients from neutron decay to extract λ , while allowing for non-SM contributions. In combination with the experimental results from the superallowed Fermi transitions (b_F and $\overline{\mathcal{F}}_T$), improved bounds on tensor contributions can be obtained. For example, with the recent limits on A from UCNA and PERKEOII Collaborations (Mendenhall *et al.*, 2013; Mund *et al.*, 2013) and neglecting right-handed neutrinos ($A_R = 0, \alpha_R = 0$), it is possible to obtain an analytical bound on α_L (Pattie, Hickerson, and Young, 2013). Allowing for right-handed neutrinos requires a fitting procedure.

A complete set of neutron correlation data has been compiled by Dubbers and Schmidt (2011). More recent results are obtained with the PERKEOII setup (Mund *et al.*, 2013) and from the UCNA Collaboration (Mendenhall *et al.*, 2013). Combined with the bounds from pure Fermi and Gamow-Teller transitions a fit can be made to obtain all relevant parameters ($\lambda, A_L, A_R, \alpha_L$, and α_R) in a consistent way. This was recently done by Wauters, García, and Hong (2014), to extract both left-handed and right-handed tensor-coupling limits. Their fitting method entails a grid search. For all α_L and α_R values, a value of χ^2 was obtained by minimizing χ^2 for the other three parameters. With this 2D χ^2 surface a contour plot can be made, by plotting the equal $\Delta\chi^2 \equiv \chi^2 - \chi_0^2$ lines, where χ_0^2 is the minimal χ^2 .

Figure 3 shows the contour plot for the 1, 2, and 3 σ ($\Delta\chi^2 = 1, 4$, and 9) bounds obtained with this method and by using the most relevant experiments listed in Table III. It is important to note that the neutron lifetime requires the value of V_{ud} . The most precise value for V_{ud} is obtained from the $\mathcal{F}t$ of superallowed decays (Hardy and Towner, 2014), under the assumption of no scalar interactions. We have corrected for this by using Eq. (A20) for the neutron lifetime. For the neutron lifetime we use the average value of the PDG (Beringer *et al.*, 2012). For the correlation coefficients the averages of the PDG cannot be used, because these are obtained by assuming only SM interaction. The possible different dependence on the Fierz-interference term is therefore not included. We consider the different values of A

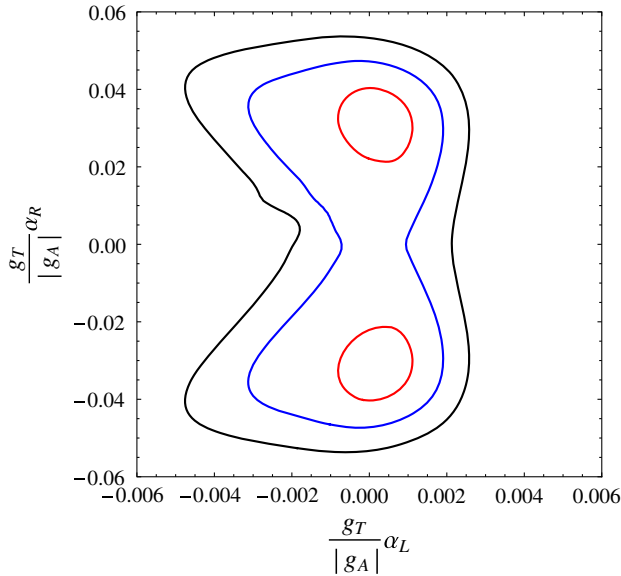


FIG. 3 (color online). Contour plot of the 1, 2, and 3 σ contours, derived from the selection of available data listed in Table III. In the fitting procedure we minimized A_L , A_R , and λ . Notice the scale difference of the two axes.

separately, for which we have calculated the energy dependence with Eq. (26). We have included the measurement of B , although for neutron decay this coefficient actually has a reduced sensitivity to the Fierz term b and to λ ; see Eq. (A26).

We find at 90% C.L.²

$$-0.3 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_L < 0.06 \times 10^{-2}, \quad (41a)$$

$$-4.6 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_R < 4.6 \times 10^{-2}, \quad (41b)$$

$$-0.1 \times 10^{-2} < \frac{g_S}{g_V} A_L < 0.3 \times 10^{-2}, \quad (41c)$$

$$-5 \times 10^{-2} < \frac{g_S}{g_V} A_R < 6 \times 10^{-2}, \quad (41d)$$

$$1.2659 < \lambda < 1.2746. \quad (41e)$$

The extracted value of λ has a much larger error compared to $\lambda = 1.2723(23)$ from PDG. The scalar bounds are the same as the bounds in Eq. (34), but the tensor bounds are improved because of the inclusion of the neutron data. Especially the positive bound for α_R is reduced as compared to Eq. (39). This is caused by the large spread in experimental values for A . Using only the two most recent values of the PERKEOII setup (Mund *et al.*, 2013) and from the UCNA Collaboration (Mendenhall *et al.*, 2013) gives $-0.3 \times 10^{-2} < g_T \alpha_L / |g_A| < 0.2 \times 10^{-2}$. For the tensor bounds, the neutron lifetime has a large influence (Wauters, García, and Hong, 2014). We therefore anticipate that the error in the neutron lifetime and the spread in A will soon give the dominant error on the limit on tensor couplings.

Recently, also mirror decays have been used to constrain tensor couplings. The strong constraint on b_F from superallowed Fermi decays can be combined with measurements on mirror nuclei, to derive a value for b_{GT} . In Severijns *et al.* (2008) a complete survey of $\mathcal{F}t$ values of the available mirror transitions is given. For $T = 1/2$ transitions the relation between the $\mathcal{F}t$ values of the mirror and superallowed $0^+ \rightarrow 0^+$ is given by (Severijns *et al.*, 2008)

$$\mathcal{F}t^{\text{mirror}} \equiv \frac{2\mathcal{F}t^{0^+ \rightarrow 0^+} \langle 1 + \frac{g_S^2}{g_V^2} [A_L^2 + A_R^2] - 2\gamma \langle \frac{m_e}{E_e} \rangle^{0^+ \rightarrow 0^+} \frac{g_S}{g_V} A_L \rangle}{1 + \frac{g_S^2}{g_V^2} [A_L^2 + A_R^2] + \frac{f_A}{f_V} \rho^2 [1 + 4\alpha_L^2 + 4\alpha_R^2] \pm 2\gamma \langle \frac{m_e}{E_e} \rangle (\frac{g_S}{g_V} A_L - 2 \frac{g_T}{|g_A|} \alpha_L \rho^2)}, \quad (42)$$

where $f_A/f_V = 1.0143(29)$ is the ratio of the axial-vector and vector statistical rate functions (Severijns *et al.*, 2008). The inverse energy dependence of the superallowed Fermi decays is denoted by $\langle m_e/E_e \rangle^{0^+ \rightarrow 0^+}$ and calculated in Pattie, Hickerson, and Young (2013). If ρ is known, a value for α_L can be extracted from $\mathcal{F}t^{\text{mirror}}$.

The mirror β^+ decay of ^{19}Ne to ^{19}F was recently studied to determine the lifetime of ^{19}Ne (Broussard *et al.*, 2014). In this work, the effectiveness of the method described above is shown. For mixed decays an independent measurement of ρ is necessary. For ^{19}Ne , $\rho = 1.5995(45)$ (Calaprice *et al.*, 1975) was derived from the measurement of the β asymmetry A . Neglecting quadratic couplings in Eq. (42) and using the extracted value $\mathcal{F}t = 1719.8(13)$ s with $\langle m_e/E_e \rangle = 0.387022(18)$ from Broussard *et al.* (2014) a limit on b_{GT}

is derived. For left-handed tensor couplings this gives at 90% C.L. (Broussard *et al.*, 2014)

$$-1.5 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_L < 0.12 \times 10^{-2}. \quad (43)$$

The bounds are only an order of magnitude less precise than the combined limits in Eq. (41) and show the potential for this kind of measurements for improving the existing bounds.

4. Tensor constraints from radiative pion β decay

Bychkov *et al.* (2009) derived limits on tensor couplings from radiative pion decay $\pi^+ \rightarrow e^+ + \nu_e + \gamma$. These bounds can be translated into bounds on α_L (Bhattacharya *et al.*, 2012) by using estimates for the pion form factor (Mateu and Portolés, 2007). Assuming no right-handed couplings and using $g_T = 1.047(61)$, a limit at 90% C.L. is found,

$$-1.9 \times 10^{-3} < \frac{g_T}{|g_A|} \alpha_L < 2.3 \times 10^{-3}. \quad (44)$$

²Bounds are extracted by scanning the 2D $\chi^2 + 1.64^2$ surface for scalar ($A_{L,R}$) and tensor ($\alpha_{L,R}$), while for λ we used the 1D probability density.

These bounds are the strongest bounds on tensor couplings from a single decay experiment and show that future β -decay experiments should probe $\alpha_L < 10^{-3}$ and beyond, in order to improve these existing limits.

5. Pseudoscalar constraints

Pseudoscalar interactions have so far been neglected in β -decay searches, since they are strongly suppressed because the nuclei are nonrelativistic. The suppression of these terms is $\mathcal{O}(1/M)$, where M is the nucleon mass. However, in β decay, the pseudoscalar interactions are always multiplied by g_P , the pseudoscalar form factor discussed in Eq. (22). The large value $g_P = 349(9)$ (González-Alonso and Camalich, 2014) largely cancels this suppression, and β -decay experiments might be used to probe these interactions. There are, however, already strong constraints on pseudoscalar couplings from pion decay (Herczeg, 1994, 2001; Bhattacharya *et al.*, 2012).

The ratio $R_\pi = \Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$ is sensitive to pseudoscalar couplings defined by

$$\mathcal{L} = \frac{G_F V_{ud}}{\sqrt{2}} [A_L^P \bar{e}(1 - \gamma_5)\nu_e + A_R^P \bar{e}(1 + \gamma_5)\nu_e] \bar{u}\gamma_5 d, \quad (45)$$

where we have neglected flavor-changing couplings, which can be found in Bhattacharya *et al.* (2012). The ratio R_π/R_π^{SM} , where R_π is the measured value, is sensitive to electron and muon pseudoscalar couplings $A^{P(e)}$ and $A^{P(\mu)}$, respectively. If these couplings are such that $A^{P(e)}/m_e = A^{P(\mu)}/m_\mu$, their contributions to the ratio cancel and no bounds on pseudoscalar interactions can be obtained. Since there is no reason to assume such a cancellation, we can place bounds on pseudoscalar interactions, because these would show up as $R_\pi/R_\pi^{\text{SM}} \neq 1$. The current best value for this ratio is $R_\pi/R_\pi^{\text{SM}} = 0.996(3)$ (Beringer *et al.*, 2012; Cirigliano and Rosell, 2007), which leads to (90% C.L.) (Bhattacharya *et al.*, 2012; Cirigliano, González-Alonso, and Graesser, 2013)

$$-1.4 \times 10^{-7} < A_L^P < 5.5 \times 10^{-4}, \quad (46a)$$

$$-2.8 \times 10^{-4} < A_R^P < 2.8 \times 10^{-4}. \quad (46b)$$

In β decay the pseudoscalar term shows up in Gamow-Teller and mixed decays. The most relevant to experiments are its contributions to the Fierz-interference term,

$$b_{\text{GT}} = \mp 4\gamma \frac{g_T}{|g_A|} \alpha_L \mp \frac{1}{3}\gamma \frac{g_P}{|g_A|} A_L^P \frac{E_0 - E_e}{M}, \quad (47)$$

which enters with the usual $\langle m_e/E_e \rangle$ suppression. The $(E_0 - E_e)/M$ term is responsible for the suppression of pseudoscalar contributions, however, because $g_P(E_0 - E_e)/M \simeq 0.4$ pseudoscalar interactions are still suppressed compared to tensor interactions. Given the current limit on α_L , improving the bounds in Eq. (46a) seems unlikely in the near future.

The pseudoscalar couplings in Eq. (46) can also be translated into bounds on scalar and tensor couplings. If scalar and tensor interactions are present at the new-physics scale Λ , they will mix via radiative loop corrections,

and pseudoscalar couplings will radiatively be generated (Herczeg, 1994; Campbell and Maybury, 2005). Current limits are at the level of (Bhattacharya *et al.*, 2012; Cirigliano, González-Alonso, and Graesser, 2013; Cirigliano, Gardner, and Holstein, 2013)

$$|A_L| \lesssim 8 \times 10^{-2} \quad \text{and} \quad |A_R| \lesssim 5 \times 10^{-2}, \quad (48a)$$

$$|\alpha_L| \lesssim 2 \times 10^{-3} \quad \text{and} \quad |\alpha_R| \lesssim 1.2 \times 10^{-3}, \quad (48b)$$

and depend logarithmically on the scale of new physics Λ , for which $\Lambda = 10$ TeV is used. These bounds are of the same order of magnitude as global-fit limits from β decay in Eq. (41), except for the bound on α_R , which is an order of magnitude better. However, because the constraints for right-handed currents rely on the flavor structure of new physics (Cirigliano, González-Alonso, and Graesser, 2013), we do not further consider these bounds.

6. Left-handed scalar versus tensor

In Sec. IV.C we discuss exotic couplings involving right-handed neutrinos. If right-handed neutrinos are absent, or too heavy to be energetically allowed in β decay, right-handed neutrino couplings, i.e., A_R and α_R , can be neglected. The resulting reduction of parameter space allows us to use mixed decays to fit the correlations between left-handed tensor and scalar couplings. Figure 4 shows these correlations. For the complete set of data listed in Table III we find at 90% C.L.

$$-0.1 \times 10^{-2} < \frac{g_S}{g_V} A_L < 0.3 \times 10^{-2}, \quad (49a)$$

$$-0.2 \times 10^{-2} < \frac{g_T}{|g_A|} \alpha_L < 0.06 \times 10^{-2}, \quad (49b)$$

$$1.2715 < |\lambda| < 1.2744. \quad (49c)$$

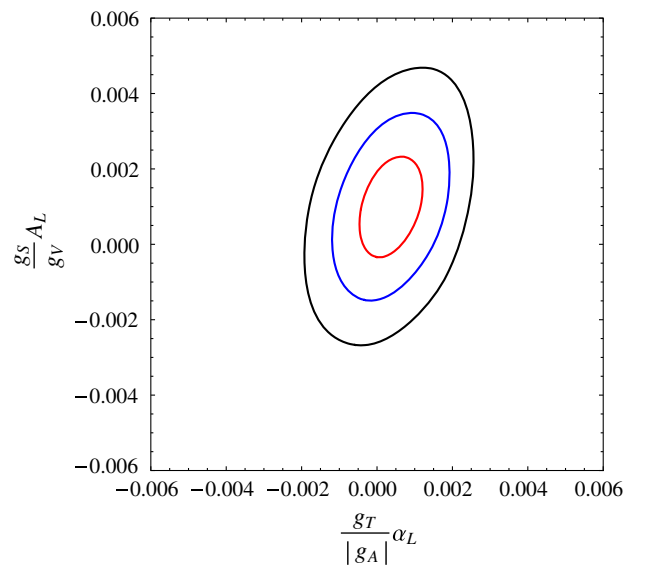


FIG. 4 (color online). Contour plot of the 1, 2, and 3 σ contours, derived from the selection of available data listed in Table III without right-handed couplings, i.e., $A_R = \alpha_R = 0$.

These bounds are not significantly different from the bounds from the complete fit in Eq. (41). For comparison: limits on right-handed couplings from neutron decay alone are found in Konrad *et al.* (2010) and Dubbers and Schmidt (2011).

B. Constraints from the LHC experiments

Low-energy experiments are mostly viewed as complementary to high-energy collider searches for BSM physics. Experiments at the LHC can place bounds on new physics by looking for the on-shell production of new particles, as done in searches for a W_R boson [Eq. (13)] or supersymmetric particles. We focus here on the effect of a W_R boson, because this has been studied complementarily by precision decay experiments and by the LHC, e.g., Dekens and Boer (2014). At the LHC, W_R is searched for by considering its possible decay channels. In the $W_R \rightarrow t\bar{b}$ channel, such direct searches at the CMS experiment constrain $M_R > 2$ TeV (Chatrchyan *et al.*, 2014). Constraints from the $W_R \rightarrow e\nu$ channel are similar, but depend on assumptions for the right-handed neutrino. Constraints from neutral-kaon mixing give $M_R > 3$ TeV (Bertolini, Maiezza, and Nesti, 2014).

In β decay, strong limits come from CKM unitarity tests, for which the best bound is (Hardy and Towner, 2014)

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008(56), \quad (50)$$

which uses the value of V_{us} from Moulson (2013). The error has equal contributions from V_{ud} and V_{us} . Following Hardy and Towner (2009), this leads to a constraint on a_{LR} , i.e., left-handed lepton couplings and right-handed quark couplings, of

$$-4 \times 10^{-3} < a_{LR} < 5 \times 10^{-3}, \quad (51)$$

at 90% C.L. The precision of both V_{ud} and V_{us} should improve simultaneously for such a test to remain significant.

In β decay, some correlation coefficients are sensitive to a_{LR} , a_{RL} , and a_{RR} , where the latter two are present only if light right-handed neutrinos are assumed. For example, the measurements of P_F/P_{GT} (Wichers *et al.*, 1987; Carnoy *et al.*, 1991) and A_{GT} in ^{60}Co (Wauters *et al.*, 2010) are used to constrain parameters of manifest LR -symmetric models. Such models have a P symmetry, such that for the CKM matrices $V_{ud}^L = \pm V_{ud}^R$. There is no additional spontaneous CP violation, so $\omega = 0$. In this simplified model, $a_{RL} = \pm a_{LR} \sim -\xi$ and $a_{RR} = \delta = (M_1/M_2)^2$. Measurements of P_F/P_{GT} limit the combination $\delta \cdot \xi$ and do not give additional bounds, because of the strong bound on ξ from unitarity tests given in Eq. (51). Because ξ is strongly constrained, β -decay experiments can constrain only a_{RR} and thus the mass of the W_R . Derived limits are of the order of 200 GeV (Gorelov *et al.*, 2005; Wauters *et al.*, 2010), an order of magnitude below the bound from the LHC experiments presented above. In fact, when assuming manifest LR symmetry, the strongest bound on W_R comes from the K_L-K_S mass difference, from which $W_R > 20$ TeV was derived (Maiezza and Nemevšek, 2014).

Besides constraining new physics by searching for direct on-shell production, it is also possible for colliders to constrain exotic couplings. When the mass of the non-SM particle exceeds the energy accessible at the LHC, the new

particles cannot be produced on shell, but their effects can still be found in deviations from the SM predictions. In that way, the exotic interactions in Eq. (11) will also manifest themselves in proton-proton collisions. This makes it possible for the LHC data to constrain the same tensor and scalar couplings relevant in β decay (Bhattacharya *et al.*, 2012; Cirigliano, González-Alonso, and Graesser, 2013).

In particular, the $pp \rightarrow e + \text{MET} + X$ channel is considered, where MET signifies missing transverse energy. This channel is closely related to β decay, since it involves the $\bar{u}d \rightarrow e\bar{\nu}$ process at quark level. At the LHC, both the ATLAS and CMS detectors are used to search for new physics in this channel (Aad *et al.*, 2012; Chatrchyan *et al.*, 2012), by searching for an excess of events predicted at a large lepton transverse mass cut \bar{m}_T . At large \bar{m}_T , the SM cross section approaches zero more rapidly than the cross sections for new physics, making the sensitivity to non-SM physics larger at high momenta. The total cross section is

$$\begin{aligned} \sigma(m_T > \bar{m}_T) = & \sigma_{\text{SM}}(1 + |a_{LR}|^2 + |a_{RL}|^2) + \sigma_R |a_{RR}|^2 \\ & + \sigma_S(|A_L|^2 + |A_R|^2) + \frac{1}{4}\sigma_T(|\alpha_L|^2 + |\alpha_R|^2), \end{aligned} \quad (52)$$

where σ_{SM} is the SM cross section and $\sigma_{R,S,T}$ are the cross sections for new physics. The explicit form of σ_{SM} and $\sigma_{R,S,T}$ is given, to lowest order in QCD corrections, in Cirigliano, González-Alonso, and Graesser (2013). The coefficients a_{LR} and a_{RL} cannot be constrained, because their contribution is proportional to σ_{SM} , and therefore small at large \bar{m}_T .

With the expected number of background events and the number of actual observed events, one can place an upper limit on the number of new-physics events, n_s^{up} (Bhattacharya *et al.*, 2012). This translates into an upper limit for σ , and finally into bounds on exotic couplings. First bounds were derived by Bhattacharya *et al.* (2012), and updated bounds are given in Naviliat-Cuncic and González-Alonso (2013).

The bounds are derived by using the experimental data of Khachatryan *et al.* (2014) at an integrated luminosity of 20 fb^{-1} and at a center-of-mass energy of $\sqrt{s} = 8$ TeV. Naviliat-Cuncic and González-Alonso (2013) also gave the combined limits for scalar and tensor couplings, assuming only left-handed couplings. In Table IV we give the 90% C.L. bounds, obtained by allowing one exotic interaction and putting all other couplings to zero. To compare these results with β -decay constraints, we use the values from the global fit in Eq. (41) and the form factors $g_S = 1.02(11)$ (González-Alonso and Camalich, 2014) and $g_T = 1.047(61)$

TABLE IV. Comparison between β -decay limits on left- and right-handed scalar A_L and A_R and tensor couplings α_L and α_R , constraints from the LHC data (Naviliat-Cuncic and González-Alonso, 2013), and from the neutrino mass (Ito and Prezeau, 2005). Constraints are at 90% C.L., and all couplings are assumed to be real.

	$ A_L $	$ A_R $	$ \alpha_L $	$ \alpha_R $
β decay	2.5×10^{-3}	6×10^{-2}	3×10^{-3}	4.6×10^{-2}
LHC	6×10^{-3}	6×10^{-3}	2×10^{-3}	2×10^{-3}
Neutrino	...	1×10^{-3}	...	1×10^{-3}

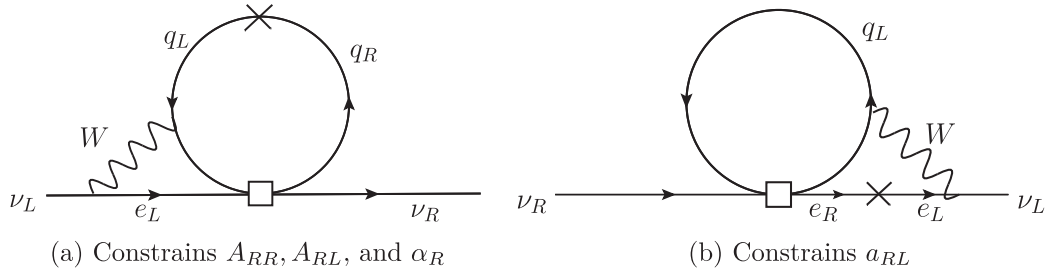


FIG. 5. The two-loop contribution to the neutrino mass, where the boxes indicate the exotic couplings. The crosses indicate mass insertions, with (a) $m_q = 4$ MeV and (b) $m_e = 0.511$ MeV (Ito and Prezeau, 2005). For Majorana neutrinos one can substitute $\nu_R \rightarrow \nu_L^c$.

(Bhattacharya *et al.*, 2014). Because the errors on the form factors are not Gaussian, we use the R -fit method described in Bhattacharya *et al.* (2012), which treats all the values in a 1σ interval with equal probability. Therefore, only the lower bounds are important. We stress again that the reduction of the error in g_S and g_T is important to make meaningful comparisons between the different experiments.

Table IV shows that the LHC constraints on left-handed couplings are comparable to β -decay constraints, while for right-handed couplings the LHC constraints are an order of magnitude better than the β -decay limits. The current status is discussed in Sec. IV.D. Naviliat-Cuncic and González-Alonso (2013) also made a projection for the 14 TeV run at 50 fb^{-1} and found that the expected bounds are a factor of 3 better.

C. Neutrino-mass implications

Besides strong bounds from the LHC experiments on right-handed interactions, there are also bounds from the neutrino mass. In the SM, neutrinos are assumed to be massless, but neutrino oscillations indicate the existence of at least two massive neutrinos. A direct upper limit on the neutrino mass comes from the shift of the end point of the β spectrum. Recent measurements of the β spectrum of ^3H give $m_\nu < 2$ eV (95% C.L.) (Kraus *et al.*, 2005; Aseev *et al.*, 2011). The experiment of the KATRIN Collaboration aims to improve these limits by an order of magnitude (Otten and Weinheimer, 2008). Other bounds on the neutrino mass are derived from cosmological observations; WMAP Collaboration (Hinshaw *et al.*, 2013) limits $\sum m_\nu < 0.44$ eV and a recent study of the Planck Collaboration (Ade *et al.*, 2014), in which Planck data are combined with neutrino oscillation data, gives a similar limit $m_\nu < 0.15$ eV, for three degenerate neutrinos.

In Eq. (11), the couplings a_{RR}, a_{RL}, A_R , and α_R involve right-handed neutrinos. These couplings can be generated only if the decay to right-handed neutrinos is kinematically allowed, i.e., if right-handed neutrinos are light enough to be created in the decay. The possibility of these light right-handed neutrinos has been considered in various new-physics scenarios as a possible dark-matter candidate. If right-handed neutrinos are very heavy, as suggested in many seesaw mechanisms, we can omit all exotic couplings with first index R .

Prezeau and Kurylov (2005) showed that the small neutrino mass also limits the presence of exotic couplings in low-energy experiments that involve a (light) right-handed neutrino (Prezeau and Kurylov, 2005). For β decay this strongly

constrains the couplings A_R, α_R , and a_{RL} (Ito and Prezeau, 2005). Neutrino masses can be either Dirac ($\bar{\nu}_L m_D \nu_R$) or Majorana ($\frac{1}{2} \bar{\nu}_L m_\nu \nu_L^c$), where $\nu_L^c = i\gamma_2 \gamma_0 \bar{\nu}_L^T$, or a combination of the two. However, the following results are general and apply to both types. Couplings to right-handed neutrinos contribute to the neutrino mass via loop interactions. Figure 5 shows the leading two-loop contribution to the neutrino mass, where the boxes indicate the non-SM couplings to right-handed particles. The crosses indicate the mass insertions needed to couple two fermions with different chiralities. Here the chirality-changing interactions are either proportional to (a) the quark or (b) the electron mass. In a power-counting scheme, one-loop contributions are in general less suppressed than two-loop contributions. However, the two-loop diagrams in Fig. 5 are enhanced by the W -boson mass, while the one-loop diagrams are suppressed only by the light-fermion mass. This makes the two-loop contribution dominant, as the additional loop suppression of $1/(4\pi)^2$ is diminished by the heavy W -boson mass.

One can estimate the two-loop contribution to the neutrino mass by considering only the logarithmic part of Fig. 5. The analytic parts are renormalization-scheme dependent and are therefore neglected (Prezeau and Kurylov, 2005). By using dimensional regularization the contribution to δm_ν is estimated as (Ito and Prezeau, 2005)

$$\delta m_\nu \approx 3g^2 G_F \bar{a} \frac{m_f M_W^2}{(4\pi)^4} \left(\ln \frac{\mu^2}{M_W^2} \right)^2, \quad (53)$$

where $\bar{a} = \{A_{RL}, A_{RR}, \alpha_R, a_{RL}\}$ are the exotic couplings from Eq. (11), $g = 0.64$ is the gauge coupling, m_f is the inserted fermion mass, and μ is the renormalization scale, which should exceed the heaviest mass in the interaction $\mu > m_t$, where m_t is the top-quark mass. Assuming that the loop corrections do not exceed the mass of the neutrino,³ i.e., $\delta m_\nu < m_\nu$, setting $m_q = 4$ MeV, $\mu = 1$ TeV, and $m_\nu < 0.15$ eV in Eq. (53) gives

$$|a_{RL}| \lesssim 10^{-2}, \quad (54a)$$

$$|A_{RR}|, |A_{RL}|, |\alpha_R| \lesssim 10^{-3}. \quad (54b)$$

³There might be scenarios in which this is not obeyed, but these scenarios would have to be fine-tuned.

In Table IV we compare these limits with current right-handed β -decay bounds and bounds from the LHC. The estimates from the neutrino mass are currently the strongest bounds on right-handed currents. They are more than an order of magnitude stronger than the β -decay bounds and comparable to the LHC bounds. For the bounds in Eq. (54) we have used the updated neutrino mass from the Planck space observatory, which might further improve in the future. The given bounds are conservative estimates, but nevertheless they show the large impact of the neutrino mass on β -decay measurements. Even stronger constraints of $\mathcal{O}(10^{-5})$ from the neutrino mass have been derived in Wang (2007).

D. Conclusions and outlook

We summarized the current status of the bounds on real right-handed vector, scalar, pseudoscalar, and tensor interactions in β decay. We compared these bounds with those obtained from proton-proton collisions at the LHC experiments and the upper limit on the neutrino mass, mainly focusing on scalar and tensor interactions. The best current bounds are given in Table IV. We distinguished between bounds on left- and right-handed scalar and tensor interactions, where left or right denotes the chirality of the neutrino. The constraints on left-handed interactions are equally constrained by the LHC and β -decay experiments. On the other hand, β -decay experiments measuring right-handed interactions would have to improve orders of magnitude to compete with the bounds from the LHC experiments and the neutrino mass. This is illustrated in Fig. 6 for scalar interactions and in Fig. 7 for tensor interactions. Table V projects the competitive accuracies required for different β -decay parameters. For left-handed currents we give the necessary precision to compete with projected future LHC bounds (Naviliat-Cuncic and González-Alonso, 2013). For right-handed bounds, we give two accuracies. The first corresponds to the required sensitivity to compete with current LHC bounds; the number in brackets corresponds to the required precision to compete with the bounds from the neutrino mass (see Table IV).

The bounds on left-handed couplings are best pursued via measurements of the Fierz-interference coefficient b . For left-handed scalar couplings A_L the bound is most stringent because of the vast effort in the study of superallowed Fermi transitions. These studies also provide the best current value for V_{ud} . The left-handed tensor coupling α_L requires a larger effort, for which several measurements need to be combined. The best current bounds are from the global fit in which neutron and nuclear data are combined. In this fit, especially the uncertainties in the neutron lifetime and the A coefficient of the neutron have a significant impact. We pointed out that the large spread in the available A measurements influences the obtained bound significantly. The Gamow-Teller part b_{GT} of the Fierz-interference term and V_{ud} can also be constrained in mirror nuclei, in analogy to the superallowed Fermi transitions. However, this also requires the measurement of at least one correlation coefficient. Measurements with this aim are undertaken (Ban et al., 2013).

In Gamow-Teller transitions, measurements of the Fierz-interference term b_{GT} allow for bounds on the left-handed

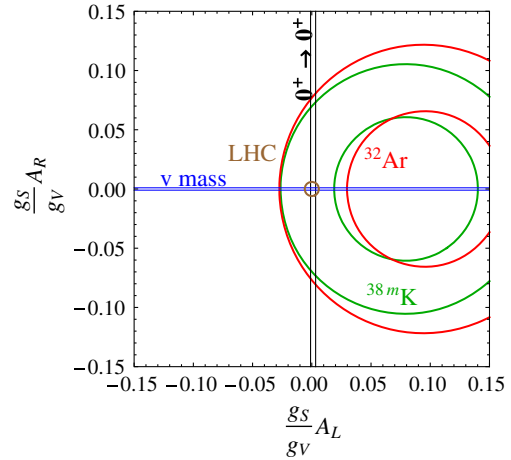


FIG. 6 (color online). Scalar bounds from nuclear β decay as in Fig. 1 combined with limits derived from the neutrino mass (horizontal lines) and constraints from the LHC experiments (circular bounds).

tensor terms. In Seattle, a ${}^6\text{He}$ factory has been set up to study this term. The lifetime of ${}^6\text{He}$ was already measured with high precision (Knecht et al., 2012), but the shell-model calculations are not sufficiently accurate as yet to search for tensor interactions. One straightforward, but not so simple, approach is to measure the decay spectrum precisely. This would give access to b_{GT} . These measurements would also have to consider contributions from the SM weak magnetism [cf. Eq. (4)]. Measurements of b_{GT} from electron-antineutrino correlation $\tilde{a}_{\beta\nu}$ and the spectrum are both ongoing and being set up (Fléclard et al., 2008, 2011; Knecht et al., 2011; Aviv et al., 2012; Naviliat-Cuncic, 2014; Severijns, 2014). If these measurements reach $b < 10^{-3}$, they would allow for a strong limit on α_L . Such a precision is necessary to compete with the projected bounds from the 14 TeV run of the LHC. In neutron decay, many efforts are undertaken to improve the measurements of $a_{\beta\nu}$ and A (Baessler et al., 2008, 2014; Märkisch et al., 2009; Počanić et al., 2009; Wietfeldt et al., 2009; Konrad et al., 2012). For comparison, limits on the Fierz terms from

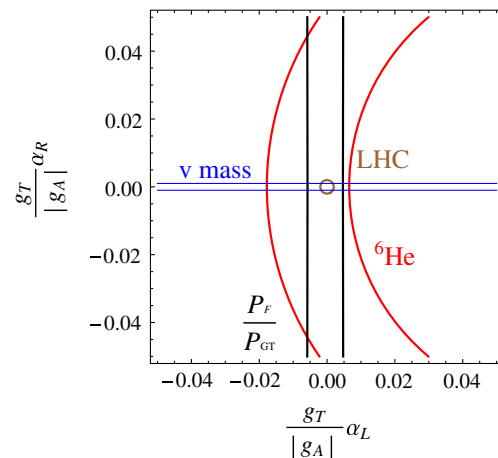


FIG. 7 (color online). Tensor bounds from nuclear β decay as in Fig. 2 combined with limits derived from the neutrino mass (horizontal lines) and constraints from the LHC experiments (circular bounds).

TABLE V. Required experimental precision on β -decay parameters to remain competitive with the LHC bounds; cf. [Naviliat-Cuncic and González-Alonso \(2013\)](#). Only the Fermi (F) and Gamow-Teller (GT) parts of the Fierz-interference term b and the β - ν correlation a are listed. The third column gives the corresponding limit on scalar couplings A_L and A_R and tensor couplings α_L and α_R . The Fierz term is the leading term in most β -correlation experiments (Sec. IV.A). The indicated bounds for b assumes that future LHC data lead to bounds indicated in the last column. The a parameter is the most direct way to obtain a bound on right-handed couplings, which should be the motivation to measure a . Here the current bounds of the LHC are assumed, while the values in parentheses are the required accuracies when the bounds derived from the limit of the neutrino mass are considered (Table IV).

Parameter	Bound	Constraint at 90% C.L.
b_{GT}	10^{-3}	$\alpha_L < 3 \times 10^{-4}$
b_F	10^{-3}	$A_L < 5 \times 10^{-4}$
a_{GT}	10^{-4} (5×10^{-6})	$\alpha_R < 6 \times 10^{-3}$ ($\alpha_R < 10^{-3}$)
a_F	8×10^{-6} (2×10^{-6})	$A_R < 2 \times 10^{-3}$ ($A_R < 10^{-3}$)

neutron decay alone are found in [Konrad *et al.* \(2010\)](#) and [Dubbers and Schmidt \(2011\)](#), including limits derived from the electron energy dependence of the β asymmetry $A_{\text{exp}}(E)$ alone.

Right-handed interactions, which imply the existence of a light right-handed neutrino, do not interfere with the SM interactions and can therefore only be measured directly, i.e., via quadratic terms. This makes it difficult to reach the sensitivity obtained for left-handed couplings. In β decay, the right-handed tensor coupling α_R can be constrained by measuring the β - ν correlation, $\tilde{a}_{\beta\nu}$. The best measurement in pure Gamow-Teller decays of $a_{\beta\nu}$ stems from the measurement in ${}^6\text{He}$ ([Johnson, Pleasonton, and Carlson, 1963](#)). Many efforts are undertaken to improve this limit in ${}^6\text{He}$ ([Knecht *et al.*, 2011](#); [Aviv *et al.*, 2012](#); [Couratin *et al.*, 2012](#)). A dedicated effort to limit right-handed tensor couplings is ongoing in ${}^8\text{Li}$, for which the daughter nucleus ${}^8\text{Be}$ breaks up into two α particles, ${}^8\text{Li} \rightarrow e^- + \bar{\nu} + 2\alpha$. The a_{GT} coefficient can be measured by measuring the β - α correlation, and by taking advantage of the increased sensitivity due to the population of a 2^+ state in ${}^8\text{Be}$. After putting the Fierz term $b = 0$, such that only right-handed interactions are constrained ([Li *et al.*, 2013](#)), one finds

$$\frac{g_T}{|g_A|} |\alpha_R| < 8 \times 10^{-2}. \quad (55)$$

The bound reaches the precision of the combined fits, but when considering the LHC or neutrino bounds the experiment would have to improve by more than 3 orders of magnitude to compete (see Table V).

When comparing tensor and scalar bounds from different fields, the form factors g_S and g_T are important. Lattice QCD calculations have made great progress and will continue to do so in the next period. The lattice prediction of g_A will hopefully reach the experimental precision soon, which would allow for a cross-check between the experimental value and the theoretical lattice value.

Besides scalar and tensor searches, we also discussed searches for $V + A$ and pseudoscalar interactions.

Pseudoscalar interactions are less suppressed than previously thought, due to the large value of g_P . However, strong bounds exist from radiative pion decay, and pseudoscalar interactions can still be neglected in the upcoming β -decay experiments. Strong constraints on $V + A$ currents are extracted from CKM unitarity tests, to which β -decay experiments contribute by providing the most accurate value of V_{ud} . Besides this, measurements of correlation coefficients can be used to constrain parameters of (manifest) left-right symmetric models. For these specific models, strong limits from the LHC experiments and the neutral-kaon mass difference exist. Therefore, the significance of β experiments in these experiments is limited to specific models.

V. LIMITS ON TIME-REVERSAL VIOLATION

So far we have considered only the real parts of the exotic couplings. In this section we focus on their imaginary parts. A nonzero measurement of an imaginary coupling would imply that time-reversal (T) symmetry and, by the CPT theorem, CP symmetry is violated.⁴ Because of the matter-antimatter asymmetry of the Universe, new sources of CP violation are expected ([Sakharov, 1967](#)). Many models of BSM physics predict such additional sources of CP violation; see, e.g., [Dekens and de Vries \(2013\)](#), [Ibrahim and Nath \(2008\)](#), and [Branco, González Felipe, and Joaquim \(2012\)](#). This makes T or CP violation one of the main portals to search for new physics. These searches range from experiments at the LHC to atomic-physics experiments. As such the observables can be quite diverse. With advances in theory, in particular, via EFT methods, relations between the different observables have become more clear (cf. Secs. IV.B and IV.C).

In this section we focus on the connection between T -violating observables in β decay and the bounds on EDMs. The P - and T -odd EDM measurements are a powerful probe of CP violation beyond the SM ([Pospelov and Ritz, 2005](#)). High-precision EDM searches have been made for the neutron, paramagnetic and diamagnetic atoms, and molecules. The EDM is a static observable, and, therefore, allows for very precise atomic-physics experiments. It is also a background-free observable, because the electroweak SM contributions to the EDM are strongly suppressed. Therefore, EDM experiments give strong limits on new T -violating physics. BSM physics contributions to the EDM can be parametrized by dimension-6 operators ([de Vries, Higa *et al.*, 2011](#); [de Vries, Mereghetti *et al.*, 2011](#); [de Vries, Timmermans *et al.*, 2011](#); [de Vries *et al.*, 2013](#); [Bsaisou *et al.*, 2015](#)). At low energy this leads to a relation between the T -violating correlations in β decay and EDMs.

Many correlation coefficients in β decay depend on the square of the underlying coupling constants. As such they depend only on the imaginary couplings squared, which are therefore difficult to access. A more direct way to probe imaginary couplings is to consider the T -odd triple correlations $\vec{J} \cdot (\vec{p}_e \times \vec{p}_\nu)$ and $\vec{\sigma}_e \cdot (\vec{J} \times \vec{p}_e)$ multiplied by the D [Eq. (17)]

⁴In any Lorentz-symmetric local field theory, CP violation is equivalent to T violation, according to the CPT theorem. For CPT violation, see Sec. VI.

and R [Eq. (18)] coefficients, respectively. The first is P even and T odd, while the latter is P and T odd. They probe left-handed imaginary couplings, which are absent in the SM.

Since the interactions contributing to D , R , and EDMs are generated by the same operators, a limit on the EDM also limits the D and R coefficients. We consider these relations and discuss the relative precision of the two types of experiments.

A. Limits on triple-correlation coefficients in β decay

A finite D coefficient arises from the interference between the imaginary parts of the left-handed vector couplings and is proportional to $\text{Im}a_{LR}$. The R coefficient arises from the interference between the imaginary parts of scalar or tensor couplings and SM couplings, making this coefficient sensitive to both $\text{Im}a_L$ and $\text{Im}\alpha_{LL}$.

The SM contributes to both the R and D coefficients through electromagnetic final-state interactions (FSI) and through SM CP violation. The FSI are only motion-reversal odd, i.e., the initial and final states are no longer interchangeable, due to radiative corrections. In this way, FSI mimic time-reversal violation, but in fact are T even. We denote their contributions by R_f and D_f and write $D = D_t + D_f$ and $R = R_t + R_f$ (Herczeg, 2005), where D_t and R_t are the true T -violating contributions. The contributions from FSI are comparable to the current experimental precision and depend on the momentum of the β particle. We will discuss their values for specific isotopes later. True T violation in the SM arises from the CP -violating phase of the CKM matrix and the QCD θ term. These sources contribute only at the level of $\mathcal{O}(10^{-12})$ (Herczeg and Khriplovich, 1997), much below the current experimental precision.

1. D coefficient

To first order in exotic couplings, the D_t coefficient can be expressed as (Jackson, Treiman, and Wyld, 1957a)

$$D_t = a_D \text{Im}a_{LR}, \quad (56)$$

from Eq. (A15), with

$$a_D = \frac{4\delta_{J'J} \sqrt{\frac{J}{J+1}} \rho}{1 + \rho^2}. \quad (57)$$

The D coefficient can be accessed only in mixed transitions and has been measured in both neutron and ^{19}Ne decays, which have $a_D = 0.87$ and $a_D = -1.03$, respectively. For ^{19}Ne the best measurement is $D = 1(6) \times 10^{-4}$ (Hallin *et al.*, 1984), and from neutron decay $D = -0.94(2.10) \times 10^{-4}$ (Mumm *et al.*, 2011; Chupp *et al.*, 2012).

The value of the FSI depends on the kinematics of the experiment. For ^{19}Ne the FSI have been derived by Callan and Treiman (1967) as $D_f = 2.6 \times 10^{-4} p_e/p_e^{\text{max}}$, which is of the same order as the experimental precision. For neutron decay the FSI were also calculated in chiral perturbation theory by Ando, McGovern, and Sato (2009). Their derivation reproduces the original result of Callan and Treiman (1967). However, Ando, McGovern, and Sato (2009) included

higher-order corrections, which are of the order of $\mathcal{O}(10^{-7})$, allowing for an accurate expression for the FSI,

$$D_f = \left(0.228 \frac{p_e^{\text{max}}}{p_e} + 1.083 \frac{p_e}{p_e^{\text{max}}} \right) \times 10^{-5} - 5.88 \frac{p_e^{\text{max}}}{p_e} \times 10^{-8}, \quad (58)$$

where the first two terms are the Callan and Treiman (1967) terms, and the last term represents the higher-order corrections. Equation (58) is accurate to better than 1%. For the current best neutron experiment the FSI are estimated at $D_f \approx 1.2 \times 10^{-5}$ (Chupp *et al.*, 2012). The uncertainty in D_f stems from the uncertainty of the β momentum in the experiment. The T -violating part of the neutron D measurement gives at 90% C.L.

$$|D_t| < 4 \times 10^{-4}, \quad (59)$$

and with $a_D = 0.87$,

$$|\text{Im}a_{LR}| < 4 \times 10^{-4}. \quad (60)$$

Given the current experimental precision, it is clear that the FSI become increasingly more important. In this respect, neutron experiments are favored over nuclei, because the FSI can be calculated with a higher precision. Eventually the accuracy to which the FSI are known will limit measurements of true T violation.

2. R coefficient

Neglecting quadratic non-SM couplings, the R_t coefficient is given by (Jackson, Treiman, and Wyld, 1957a)

$$R_t = \frac{(a_D \mp b_D)}{|g_A|} g_T \text{Im}\alpha_L - \frac{a_D}{2g_V} g_S \text{Im}a_L, \quad (61)$$

from Eq. (A16), where the upper (lower) sign is for β^- (β^+) decay, a_D is given in Eq. (57), and

$$b_D = \frac{4\lambda_{J'J}\rho^2}{1 + \rho^2}, \quad (62)$$

with $\lambda_{J'J}$ as given in Appendix A. The R coefficient can be measured in both mixed or pure Gamow-Teller transitions, where the latter limits $\text{Im}\alpha_L$. The leading contributions to the FSI are given by the Coulomb corrections calculated by Jackson, Treiman, and Wyld (1957b),

$$R_f = \frac{Z\alpha m_e}{2p_e} (\mp a_D + b_D). \quad (63)$$

The R coefficient has been measured in the pure Gamow-Teller decay of ^8Li , where $a_D = 0$ and $b_D = 4/3$. The FSI give $R_f \approx 7 \times 10^{-4}$, leading to $R_t = (0.9 \pm 2.2) \times 10^{-3}$ (Huber *et al.*, 2003). This constrains at 90% C.L.

$$g_T |\text{Im}\alpha_L| < 3 \times 10^{-3}. \quad (64)$$

The best measurement of R in a mixed decay has been obtained for neutron decay, for which $a_D = 0.87$ and $b_D = 2.2$. Kozela *et al.* (2012) found $R = (4 \pm 12 \pm 5) \times 10^{-3}$. The FSI are calculated with Eq. (63). By using the energy distribution seen by the experimental setup one obtains $R_f \simeq 6 \times 10^{-4}$ (Kozela *et al.*, 2012). The error in R_f is less than 10%. R_f can be neglected given the current experimental precision. At 90% C.L.

$$-1.1g_T \text{Im}a_L - 0.44g_S \text{Im}A_L < 2.4 \times 10^{-2}. \quad (65)$$

With the constraint given in Eq. (64) one finds at 90% C.L.

$$g_S |\text{Im}A_L| < 6 \times 10^{-2}. \quad (66)$$

3. Alternative correlations

The measurement of the D coefficient requires the detection of the recoiling nucleus instead of detecting the neutrino. This imposes strong experimental constraints on any measurement scheme. Current schemes consider atomic trapping in a magneto-optical trap, which has led to the best value for the β - ν correlation a . Measuring D requires a modification of this trap technique, to allow for a polarized sample. It will be extremely challenging to achieve high statistical precision and systematical accuracy with this technique. An alternative lies in the β - γ correlations of polarized nuclei (Curtis and Lewis, 1957; Morita and Morita, 1957), where the photon with momentum \vec{k} is emitted from the state populated by the β decay. In this way one measures the correlation proportional to

$$E\vec{J} \cdot (\vec{p}_e \times \vec{k})(\vec{J} \cdot \vec{k}), \quad (67)$$

when the emission is due to an $E1$ transition. The correlation coefficient $E \propto \text{Im}a_{LR}$ is nonzero only for mixed decays. Young *et al.* (1995) have identified ^{36}K as a promising candidate for such a measurement, since this isotope allows for the comparison between a mixed and a Gamow-Teller transition. The latter is insensitive to T violation and can be used to test the experimental setup and reduce systematic errors. Secondary beams of high intensity can be produced, stopped, and polarized in a buffer gas allowing one to measure β - γ correlations (Müller *et al.*, 2013) with high precision. Correlations alternative to measuring R are also possible [the L and M coefficients (Ebel and Feldman, 1957; Jackson, Treiman, and Wyld, 1957a)] but, similar to R , will always require one to measure the polarization of the β particle, which is an inefficient process.

In radiative β decay, it is possible to have triple-correlation coefficients without nuclear or electron spin (Braguta, Likhoded, and Chalov, 2002; Gardner and He, 2012, 2013), such as

$$K\vec{k} \cdot (\vec{p}_\nu \times \vec{p}_e). \quad (68)$$

This coefficient has not been measured, but Dekens and Vos (2015) showed that EDMs provide extremely strong constraints on the coefficient K .

TABLE VI. The current best EDM limits of the neutron, diamagnetic Hg, paramagnetic Tl, and molecular YbF and ThO. The neutron EDM and Hg can be connected to the D coefficient (and E coefficient). Other EDM measurements, except the neutron, can be connected to the R coefficient. The limit from molecular YbF and ThO are expressed as a constraint on the electron EDM d_e .

EDM	e cm (90% C.L.)	Reference	Connection to β decay
n	2.9×10^{-26}	Baker <i>et al.</i> (2006)	D
^{199}Hg	2.6×10^{-29}	Griffith <i>et al.</i> (2009)	D, R
^{205}Tl	0.9×10^{-24}	Regan <i>et al.</i> (2002)	R
YbF	$ d_e < 10.5 \times 10^{-28}$	Hudson <i>et al.</i> (2011)	R
ThO	$ d_e < 8.7 \times 10^{-29}$	Baron <i>et al.</i> (2014)	R

B. EDM limits

Limits exist for the neutron EDM, the electron EDM, and several atomic EDMs. The best current bounds are listed in Table VI, where the limits from molecular YbF and ThO are expressed as a limit on the electron EDM d_e . The last column of Table VI indicates if a connection to the triple-correlation coefficients D and R exists (Khriplovich, 1991; Ng and Tulin, 2012).

1. Limits on D from EDM limits

Any new vector interaction that contributes to $\text{Im}a_{LR}$ (and thus to D_t) also contributes to nuclear EDMs (Herczeg, 2005; Ng and Tulin, 2012). This makes it possible to translate bounds on the EDMs of the neutron and diamagnetic atoms into bounds on $\text{Im}a_{LR}$. The D coefficient is P even and T odd, while the EDM is both P and T odd. Nevertheless, loop corrections, containing the W boson, allow for a relation between these observables.

The relevant CP -odd dimension-6 operator is (Ng and Tulin, 2012)

$$\mathcal{L}^{(\text{eff})} = \frac{c}{\Lambda^2} \bar{u}_R \gamma^\mu d_R \tilde{\varphi}^\dagger i D_\mu \varphi + \text{H.c.}, \quad (69)$$

where c is a complex coefficient, Λ is the scale of new physics, D_μ is the covariant derivative, and φ is the Higgs doublet with $\tilde{\varphi}^I = \epsilon^{IJ} \varphi^{J*}$, where ϵ^{IJ} is the antisymmetric tensor. Figure 8 shows the energy evolution of this operator. First, electroweak symmetry breaking generates the coupling of the W boson to right-handed quarks,

$$\mathcal{L}^{(\text{eff})} = \frac{gv^2}{2\sqrt{2}\Lambda^2} (c \bar{u}_R \gamma^\mu d_R W_\mu^+ + c^* \bar{d}_R \gamma^\mu u_R W_\mu^-), \quad (70)$$

where φ acquired its vacuum-expectation value $v/\sqrt{2}$ and g is the $SU(2)_L$ coupling constant. The W boson can couple to a lepton current or a quark current. At lower energy, the W boson is integrated out. This generates a P - and T -odd four-quark coupling and the lepton-quark coupling a_{LR} in β decay. The effective Lagrangian is

$$\mathcal{L}^{(\text{eff})} = -\frac{c}{\Lambda^2} (\bar{u}_R \gamma^\mu d_R \bar{e}_L \gamma_\mu \nu_{eL} + V_{ud} \bar{u}_R \gamma^\mu d_R \bar{d}_L \gamma_\mu u_L) + \text{H.c.}, \quad (71)$$

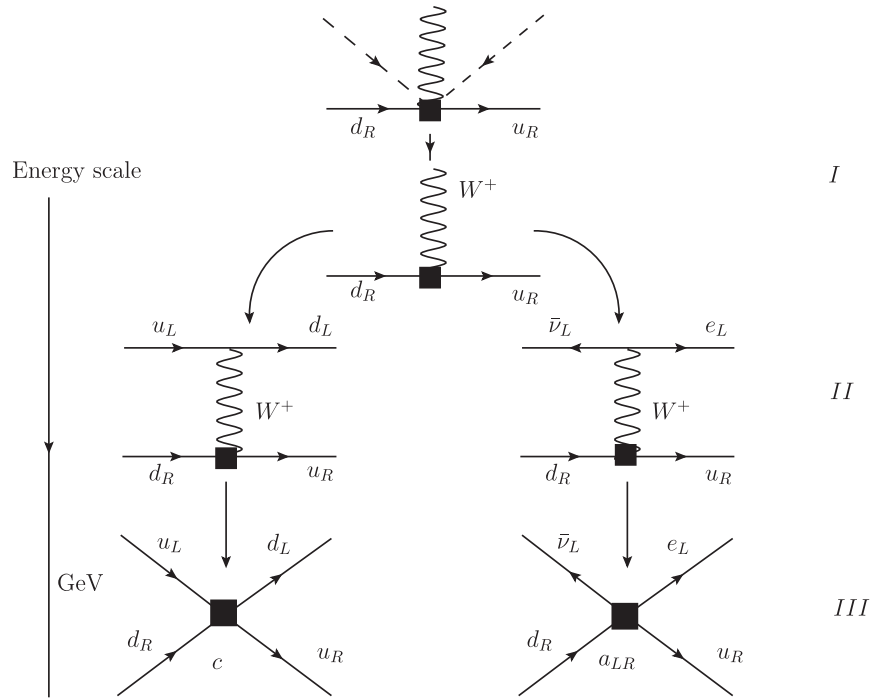


FIG. 8. Generation of the four-fermion operators that contribute to the EDM (left) and β decay (right). The boxes denote the four-fermion couplings c and a_{LR} , respectively. The coupling of the W boson to the right-handed quarks is generated by the dimension-6 operator in Eq. (69).

which shows that the two couplings c and a_{LR} have a common origin. They are related by

$$\text{Im}a_{LR} = \frac{\text{Im}c}{2\sqrt{2}G_F\Lambda^2}. \quad (72)$$

When evolving to the QCD scale, the second term in Eq. (71) is affected by QCD renormalization. However, this has only a small numerical effect (Dekens and de Vries, 2013), which can be neglected given the uncertainties coming from the calculation of the neutron EDM.

Bounds on $\text{Im}c$ thus lead to an upper limit on $\text{Im}a_{LR}$. The dependence of the EDM on $\text{Im}c$ involves theoretical calculations at different energy scales. Especially for diamagnetic atoms such as ^{199}Hg , differences in nuclear calculations lead to a large uncertainty in the interpretation of the bounds on atomic EDMs. Therefore, we do not consider bounds from ^{199}Hg . No such problem occurs for the neutron, and de Vries *et al.* (2013) and Seng *et al.* (2014) estimated the link between the neutron EDM and $\text{Im}c$ as

$$d_n = -1 \times 10^{-20} \frac{\text{Im}c}{2\sqrt{2}G_F\Lambda^2} e \text{ cm}. \quad (73)$$

This result differs by an order of magnitude from the result used by Ng and Tulin (2012), which was obtained from He and McKellar (1993) and An, Ji, and Xu (2010). de Vries *et al.* (2013) and Seng *et al.* (2014) pointed out that, due to the use of a relativistic meson-nucleon field theory, He and McKellar (1993) and An, Ji, and Xu (2010) overestimated the neutron EDM by an order of magnitude.

The current bound on the neutron EDM $|d_n| < 2.9 \times 10^{-26} e \text{ cm}$ (Baker *et al.*, 2006) and Eq. (73) gives at 90% C.L.

$$|\text{Im}a_{LR}| < 3 \times 10^{-6}. \quad (74)$$

This bound is at least 2 orders of magnitude below the bound obtained from β decay. Improving this bound in β decay requires a measurement of $D_t < 10^{-6}$, which is an order of magnitude below the contribution of the FSI.

The result above is obtained in a model-independent EFT approach, by introducing dimension-6 operators. The constraints apply to left-right symmetric models, exotic fermion models, and the R -parity violating minimal supersymmetric standard model (MSSM) (Ng and Tulin, 2012). Evasion of the bounds in Eq. (74) is possible only in either a strongly fine-tuned model or in a model in which the dimension-6 operators do not exist or do not contribute to either EDMs or β decay. An example of the latter is leptoquarks (LQs). LQs are particles with both baryon and lepton numbers, which can be either vector or scalar particles depending on their spin. These were previously considered “EDM safe,” but in fact they are not (Ng and Tulin, 2012). LQs can contribute to β decay at tree level, for example, via the exchange of scalar LQs as depicted in Fig. 9(a). Leptoquarks also contribute to EDMs, but only the W exchange [Fig. 9(b)]. Ng and Tulin (2012) showed that these loop contributions are not suppressed by the light-quark masses $m_{u,d}^2$, as was previously argued (Herczeg, 2001). Therefore, the constraints from EDMs in the LQ scenario are much more stringent than previously thought.

Estimates of the limit on D_t in this scenario depend on the LQ mass and on whether light right-handed neutrinos exist.

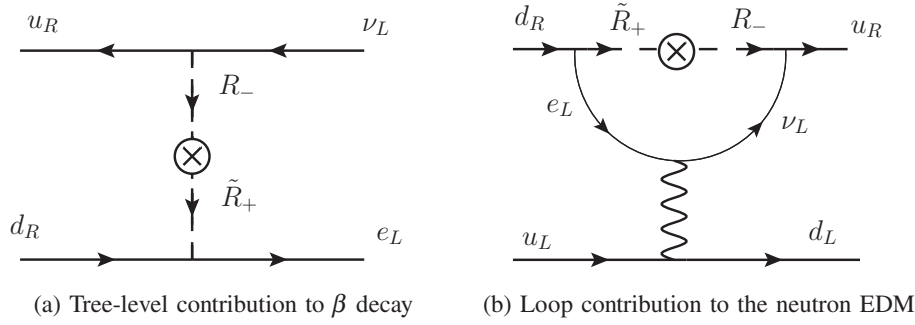


FIG. 9. Example of scalar LQ exchange that contributes to (a) β decay at tree level, and to (b) the neutron EDM via an electroweak loop. The scalar LQ are denoted by R_- and \tilde{R}_+ , where \pm refers to the weak isospin component. After Ng and Tulin, 2012.

Assuming the existence of light right-handed neutrinos, Ng and Tulin (2012) found

$$\text{Im}a_{LR} = D_t/a_D < 3 \times 10^{-4} \left(\frac{300 \text{ GeV}}{m_{LQ}} \right)^2, \quad (75)$$

while without them

$$\text{Im}a_{LR} = D_t/a_D < 7 \times 10^{-5} \left(\frac{300 \text{ GeV}}{m_{LQ}} \right)^2. \quad (76)$$

Ng and Tulin (2012) conservatively took $m_{LQ} = 300 \text{ GeV}$, which would give, assuming the existence of light right-handed neutrinos, $D_t < 3 \times 10^{-4}$, a limit of the same order as the current β -decay bounds. Nevertheless, improving the current β -decay limit seems a difficult task, since there are many experiments ongoing or planned that aim to improve the bounds on the neutron EDM (Ito, 2007; Altarev *et al.*, 2009, 2012; Serebrov *et al.*, 2009; van der Grinten *et al.*, 2009; Baker *et al.*, 2011). In addition, strong bounds on the scalar LQ mass exist from the ATLAS and CMS experiments at the LHC. The bounds on their masses range from 607 to 830 GeV, depending on the assumed LQ branching ratio (Olive *et al.*, 2014), which suggests much stronger bounds on D_t .

2. Limits on R from EDM limits

The R coefficient and the EDM are both P and T odd. EDM measurements in atoms and molecules limit both the electron EDM and BSM scalar and tensor electron-nucleon interactions. Khriplovich (1991) showed the relation between these electron-nucleon interactions and the electron-quark interaction of β decay. The scalar and tensor electron-nucleon interactions are defined by

$$\mathcal{L} = \sum_N \frac{G_f}{\sqrt{2}} [C_S \bar{N} N \bar{e} i \gamma_5 e + C_T \bar{N} \sigma_{\mu\nu} N \bar{e} i \gamma_5 \sigma^{\mu\nu} e], \quad (77)$$

where C_S (C_T) is the scalar (tensor) coupling and we have neglected pseudoscalar couplings. Khriplovich (1991) and Khriplovich and Lamoreaux (1997) showed that the limits on C_S and C_T can be related to both $\text{Im}A_L$ and $\text{Im}a_{LL}$, the couplings contributing to the R coefficient.

The best current limit on nucleon scalar couplings is due to the EDM limit on molecular ThO, $|C_S| < 5.9 \times 10^{-9}$ (90% C.L.) (Baron *et al.*, 2014). The best bound on the nucleon tensor coupling $|C_T| < 1.3 \times 10^{-9}$ (90% C.L.) is derived from the EDM limit on atomic Hg (Ginges and Flambaum, 2004; Griffith *et al.*, 2009). These couplings must be translated to quark couplings in order to compare them to the β -decay couplings in Eq. (11). At the quark level, scalar and tensor couplings in the electron-quark (e - q) interaction are described by (Herczeg, 2003)

$$\mathcal{L} = \sum_{q=u,d} \frac{G_F}{\sqrt{2}} [k_{Sq} (\bar{e} i \gamma_5 e \bar{q} q) + k_{Tq} (\bar{e} i \gamma_5 \sigma_{\mu\nu} e \bar{q} \sigma^{\mu\nu} q)], \quad (78)$$

where k_{Sq} (k_{Tq}) is the scalar (tensor) coupling in the e - q interaction. The nucleon couplings can be translated into quark couplings by using the calculations in Herczeg (2003, 2005), which show that nucleon and quark couplings are of the same order of magnitude. Conservatively, we find that the k_{Sq} and k_{Tq} couplings are $< 10^{-8}$ (90% C.L.)

Figure 10 shows that the electroweak corrections to the exotic β -decay couplings contribute to the EDM e - u couplings, k_{Su} and k_{Sd} . The effective P - and T -odd e - u interactions in Fig. 10 are estimated as (Khriplovich, 1991)

$$\begin{aligned} & \frac{-G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \ln \left(\frac{\mu^2}{M_W^2} \right) V_{ud} \text{Im}(2A_L + 24\alpha_L) \\ & \times \left[\bar{e} i \gamma_5 e \bar{u} u + \frac{1}{2} \bar{e} i \gamma_5 \sigma_{\mu\nu} e \bar{u} \sigma^{\mu\nu} u \right], \end{aligned} \quad (79)$$

where μ is the renormalization scale. Limits on the scalar electron-nucleon interaction C_S thus limit both A_L and α_L . The effective e - d interaction contains only A_L and gives similar constraints.

Comparing Eqs. (78) and (79) we arrive at an expression for k_{Su} and k_{Tu} . By using $k_{Su} < 10^{-8}$ (90% C.L.) and the conservative assumption that $\ln(\mu^2/m_W^2) = 1$ as in Khriplovich (1991), we estimate that at 90% C.L.

$$|\text{Im}A_L| < 10^{-5}, \quad (80a)$$

$$|\text{Im}\alpha_L| < 10^{-6}. \quad (80b)$$

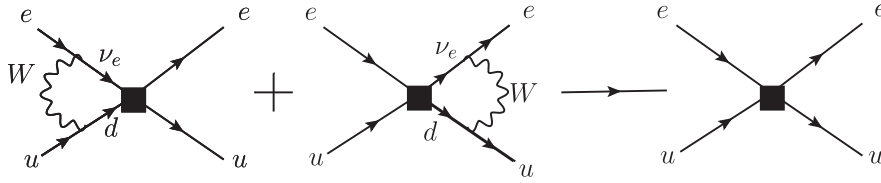


FIG. 10. Contribution of β -decay coupling to the effective P - and T -odd electron-quark couplings through the exchange of the W boson.

Both bounds are at least 2 orders of magnitude better than those obtained from the R coefficient in β decay.

C. Conclusion

Table VII summarizes the limits on imaginary couplings. Bounds obtained from EDMs are several orders of magnitude better than current bounds from T -violating β -decay coefficients. The many ongoing efforts in the EDM field will strengthen the EDM bounds even further.

The D coefficient should be measured with a precision of 10^{-6} to improve the current EDM limits. Such a measurement is below the FSI interactions and would require precise knowledge of the FSI for the used isotope. Measurements of the D coefficient are considered as part of a larger effort to measure 11 coefficients (R) in neutron decay (Bodek *et al.*, 2011). Measurements of D are also considered in nuclear decays (Behr *et al.*, 2014; Liénard, 2014). The E coefficient in Eq. (67) depends on the same BSM coupling as the D coefficient and is thus subject to the same EDM constraints.

It might be possible that the connection between EDMs and β decay is diminished in a specific new-physics model, when such a model is strongly fine-tuned. For the D coefficient examples are leptoquark models. Conservatively, this model relaxes the EDM constraint by maximally 2 orders of magnitude to $|D_t| < 3 \times 10^{-4}$ (Ng and Tulin, 2012). This is of the same order as current β -decay limits. Direct bounds on leptoquarks from the LHC experiments already suggest a stronger bound. Besides that, new bounds on the neutron EDM are also expected before any new D measurement could realistically be done. This would further improve the bounds in Table VII.

Improving the current bounds on $\text{Im}\alpha_L$ requires a measurement of $R_t < 10^{-6}$, which is an improvement of the current result by more than 3 orders of magnitude. An R measurement in ^8Li is ongoing at the Mott polarimeter for T violation (MTV) (Totsuka *et al.*, 2014). Specific models may again weaken the connection between β decay and EDMs. Such models would have to be strongly fine-tuned. For example,

TABLE VII. Comparison between β -decay limits on imaginary couplings and constraints from EDMs. The bound in parentheses is derived in a model with leptoquarks and right-handed neutrinos. For the β -decay coefficients we use $g_S = 1.02(11)$ (González-Alonso and Camalich, 2014) and $g_T = 1.047(61)$ (Bhattacharya *et al.*, 2014) and the R fit mentioned in Sec. IV.B. Constraints are at 90% C.L.

	$\text{Im}\alpha_{LR}$	$\text{Im}\alpha_L$	$\text{Im}\alpha_L$
β decay	4×10^{-4}	6×10^{-2}	3×10^{-3}
EDM	3×10^{-6} (3×10^{-4})	10^{-5}	10^{-6}

Herczeg (2005) showed that in R -parity violating SUSY (Herczeg, 2005) such a cancellation would have to occur over 3 orders of magnitude. Such a severe cancellation is highly unnatural. Besides EDM limits there are also strong limits from the ratio $R_\pi = \Gamma(\pi \rightarrow e\nu)/\Gamma(\pi \rightarrow \mu\nu)$, which give $\text{Im}\alpha_L < 4 \times 10^{-4}$ (Herczeg, 1995, 2005).

Our EFT approach applies only when new physics can be parametrized by the heavy scale of new physics. If new particles are very light, the EFT approach does not apply anymore. However, the absence of experimental evidence for such light degrees of freedom supports the validity of the EFT approach. We therefore conclude that new measurements of the D and R coefficients should take the EDM bounds into account and stress that the bounds can be evaded only in specific and strongly fine-tuned models.

VI. LORENTZ VIOLATION

We now review the new field of searches for the violation of Lorentz symmetry in the weak interaction. Recently, it was found that β decay offers unique possibilities to test Lorentz and/or CPT invariance in the weak interaction, in both the gauge and neutrino sectors. We discuss these two sectors separately.

A. Gauge sector

In the gauge sector, Lorentz violation can be studied in a general theoretical framework, developed to study allowed and forbidden β decay and orbital electron capture (Noordmans, Wilschut, and Timmermans, 2013a, 2013b; Vos, Wilschut, and Timmermans, 2015b). This framework considers a broad class of Lorentz-violating effects on the W boson, by adding a general tensor $\chi^{\mu\nu}$ to the Minkowski metric. At low energies, this modifies the W -boson propagator to

$$\langle W^{\mu+} W^{\nu-} \rangle = \frac{-i(g^{\mu\nu} + \chi^{\mu\nu})}{M_W^2}, \quad (81)$$

where $g^{\mu\nu}$ is the Minkowski metric and M_W is the W -boson mass. Vertex corrections are described by

$$-i\Gamma = -ig(g^{\mu\nu} + \chi^{\mu\nu}). \quad (82)$$

However, such vertex modifications also require the modification of the electron and neutrino spinors (Noordmans, Wilschut, and Timmermans, 2013b). We restrict ourselves to propagator corrections, for which Hermiticity of the Lagrangian implies that $\chi_{\mu\nu}^*(p) = \chi_{\nu\mu}(-p)$. In terms of the SME discussed in Sec. II.B, one finds, at lowest order,

$$\chi^{\mu\nu} = -k_{\phi\phi}^{\mu\nu} - \frac{i}{2g} k_{\phi W}^{\mu\nu} + 2k_W^{\rho\mu\sigma\nu} \frac{q_\rho q_\sigma}{M_W^2}, \quad (83)$$

where q is the momentum of the W boson and g is the $SU(2)$ coupling constant.

Bounds on χ have been derived from allowed (Bodek *et al.*, 2014; Müller *et al.*, 2013; Wilschut *et al.*, 2013) and forbidden β decay (Noordmans, Wilschut, and Timmermans, 2013a), pion decay (Altschul, 2013; Noordmans and Vos, 2014), muon decay (Noordmans *et al.*, 2015), and nonleptonic kaon decay (Vos *et al.*, 2014). Here we discuss allowed and forbidden β decay.

1. Allowed β decay

For allowed β decay, Noordmans, Wilschut, and Timmermans (2013b) derived the Lorentz-violating differential decay rate using the modified W -boson propagator in Eq. (81). The complete expression is given in Eq. (B1). Lorentz violation gives many additional correlations, since the observables

(momentum and spin) can now also couple to the tensor χ . In β decay, a variety of correlations can be used to access different (combinations of) χ components. The necessary expressions can be derived by integrating over one or more kinematic variables. Momentum-dependent terms are always suppressed by some power of a heavy mass (M_W in the least-suppressed case) and can therefore be neglected given the current experimental precision. Neglecting momentum-dependent contributions to the propagator, the relation $\chi_{\mu\nu}^*(p) = \chi_{\nu\mu}(-p)$ implies that χ can only be real and symmetric or imaginary and antisymmetric, i.e., $\chi_r^{0l} = \chi_r^{l0}$, $\chi_i^{0l} = -\chi_i^{l0}$, $\chi_i^{\mu\mu} = 0$, $\chi_r^{lk} = \chi_r^{kl}$, and $\chi_i^{lk} = -\chi_i^{kl}$. The subscripts r and i denote the real and imaginary parts of χ , respectively. This leaves 15 independent CPT -even components of $\chi^{\mu\nu}$ that need to be measured.

With this simplification and in the absence of tensor polarizations, the decay rate is (Noordmans, Wilschut, and Timmermans, 2013b; Vos, Wilschut, and Timmermans, 2015a)

$$\begin{aligned} dW = \frac{F(\pm Z, E_e)}{(2\pi)^5} |\vec{p}_e| E_e (E_e - E_0)^2 dE_e d\Omega_e d\Omega_\nu \bar{\xi} \left\{ 1 + (2a - c') \chi_r^{00} + (-(2a - c') \chi_r^{0l} + 2\check{g} \chi_i^{0l}) \frac{p_e^l}{E_e} \right. \\ + \frac{p_e^j p_e^l}{E_e E_\nu} [(a + c' + 2\check{a} \chi_r^{00}) \delta_{jl} - 4\check{g} \chi_r^{jl}] - (2a - c') \chi_i^{0s} \frac{(\vec{p}_\nu \times \vec{p}_e)^s}{E_e E_\nu} \\ + \frac{\langle J^k \rangle}{J} \left(-2\check{L} \chi_i^{jk} + \frac{p_e^l}{E_e} [(A + B \chi_r^{00}) \delta_{kl} - B \chi_r^{kl}] \right) + A \chi_i^{0s} \frac{(\vec{p}_e \times \langle \vec{J} \rangle)^s}{J E_e} \\ \left. + \frac{p_e^j}{E_\nu} ((-2a + c') \chi_r^{0j} - 2\check{g} \chi_i^{0j}) + \frac{\langle J^k \rangle p_e^j}{J E_\nu} [(B + A \chi_r^{00}) \delta_{kj} - A \chi_r^{kj}] - B \chi_i^{0s} \frac{(\vec{p}_\nu \times \langle \vec{J} \rangle)^s}{J E_\nu} \right\}, \quad (84) \end{aligned}$$

where $\langle \vec{J} \rangle$ is the expectation value of the spin of the parent nucleus $\tilde{\chi}^l = \epsilon^{lmk} \chi^{mk}$, and Latin indices run over spatial directions. The last line of Eq. (84) contains only the neutrino momentum or the neutrino momentum and the nuclear polarization, and can therefore mostly be ignored. In fact, the neutrino correlations give access to a similar combination of χ components as the electron correlations. The latter are considerably easier to obtain, and we further consider only the electron correlations.⁵ The coefficients $\bar{\xi}$, a , A , and B are the standard β -decay coefficients listed in Appendix A, and the coefficient c' is a modified c coefficient. The coefficients with a breve ($\check{}$) multiply Lorentz-violating coefficients. They are given by

$$\begin{aligned} c' = \frac{\rho^2}{1 + \rho^2} \bar{\Lambda}_{J'J}, \quad \check{g} = \frac{\frac{1}{3}\rho^2}{1 + \rho^2} + \frac{1}{2} c', \\ \check{L} = \pm \frac{\frac{1}{2}\lambda_{J'J}\rho^2}{1 + \rho^2}, \quad \check{a} = \frac{1 + \frac{1}{3}\rho^2}{1 + \rho^2} + \frac{1}{2} c', \quad (85) \end{aligned}$$

where the upper (lower) sign refers to β^\mp decay, and $\lambda_{J'J}$ and

$$\bar{\Lambda}_{J'J} = \Lambda_{J'J} \frac{\langle (\vec{J} \cdot \vec{J})^2 \rangle - \frac{1}{3} J(J+1)}{J(2J-1)}$$

are the standard β -decay coefficients given in Eqs. (A6) and (A7), respectively. The coefficient c' vanishes for nonoriented nuclei and for nuclei with $J' = J = 1/2$.

The effect of Lorentz violation in β decay can already be studied by measuring the dependence of the decay rate as a function of the direction of the emitted β particles. The modified Fermi decay rate integrated over neutrino energy and direction and summed over electron spin is

$$dW_F = dW^0 \left(1 + 2\chi_r^{00} - 2\chi_r^{0l} \frac{p_e^l}{E_e} \right), \quad (86)$$

while for Gamow-Teller transitions of randomly oriented nuclei

$$dW_{GT} = dW^0 \left(1 - \frac{2}{3} \chi_r^{00} + \frac{2}{3} (\chi_r^{l0} + \tilde{\chi}_i^{l0}) \frac{p_e^l}{E_e} \right), \quad (87)$$

where

$$dW^0 = \frac{1}{8\pi^4} p_e E_e (E_0 - E_e)^2 F(\pm Z, E_e) dE_e d\Omega_e \bar{\xi}. \quad (88)$$

⁵In electron capture, the neutrino correlations play an important role (Vos, Wilschut, and Timmermans, 2015b).

The component $\tilde{\chi}_i$ can also be accessed by measuring the Gamow-Teller decays of polarized nuclei as a function of the spin direction,

$$dW_{\text{GT}} = dW^0 \left(1 - \frac{2}{3} \chi_r^{00} \mp \lambda_{J'J} \tilde{\chi}^l \frac{\langle J^l \rangle}{J} \right). \quad (89)$$

As an example of a mixed decay, one has for the neutron $a = -0.11$, $A = -0.12$, $B = 0.98$, and $\check{g} = \check{L} = \lambda^2 / (1 + 3\lambda^2) = 0.27$. Integrated over the neutrino direction⁶

$$dW = dW^0 \left\{ 1 - 0.21 \chi_r^{00} + (0.21 \chi_r^{0l} + 0.55 \tilde{\chi}_i^l) \frac{p_e^l}{E_e} + \frac{\langle J^k \rangle}{J} \left[-0.55 \tilde{\chi}_i^k + (-0.12 + 0.98 \chi_r^{00}) \frac{p_e^k}{E_e} - 0.98 \chi_r^{lk} \frac{p_e^l}{E_e} \right] - 0.12 \chi_i^{0s} \frac{(\vec{p}_e \times \vec{J})^s}{JE_e} \right\}. \quad (90)$$

Equation (84) depends on SM parameters, which are often not known better than at the 1%–0.1% level. This dependence on SM coefficients can be avoided by measuring asymmetries that do not depend on the accuracy of the SM coefficients. The Lorentz-violating part of Eq. (86) can, for example, be accessed by measuring the decay asymmetry of a Fermi transition with the β particles measured in opposite directions,

$$A_F = \frac{W_F^+ - W_F^-}{W_F^+ + W_F^-} = -2\beta \chi_r^{0l} \hat{p}_e^l, \quad (91)$$

where $\beta = |\vec{p}_e|/E_e$ and W_F^\pm is the rate of β particles measured in the $\pm \hat{p}_e$ direction. Similarly, the decay asymmetry in Gamow-Teller decays is

$$A_{\text{GT}} = \frac{W_{\text{GT}}^+ - W_{\text{GT}}^-}{W_{\text{GT}}^+ + W_{\text{GT}}^-} = \frac{2}{3} \beta (\chi_r^{0l} + \tilde{\chi}_i^l) \hat{p}_e^l. \quad (92)$$

The coefficient $\tilde{\chi}$ can also be obtained by measuring the spin asymmetry in a pure Gamow-Teller transition

$$A_J = \frac{W_{\text{GT}}^{\uparrow} - W_{\text{GT}}^{\downarrow}}{W_{\text{GT}}^{\uparrow} + W_{\text{GT}}^{\downarrow}} = P A \tilde{\chi}_i^k j^k, \quad (93)$$

where $W_{\text{GT}}^{\uparrow(\downarrow)}$ are the integrated decay rates independent of the β direction, but in the inverted polarization direction \vec{j} , and P is the degree of nuclear polarization. A is the β asymmetry coefficient (for Gamow-Teller decays $A = \mp \lambda_{J'J}$). The remaining components of χ require more complicated measurements that involve at least two observables. The decay asymmetry between the spin and the β particles can, for example, be measured from

$$A_{J\beta} = \frac{W_L^{\uparrow} W_R^{\downarrow} - W_R^{\uparrow} W_L^{\downarrow}}{W_L^{\uparrow} W_R^{\downarrow} + W_R^{\uparrow} W_L^{\downarrow}} = 2P\beta (A \chi_i^{0s} e^{s lk} - B \chi_r^{lk}) \hat{p}_e^l j^k, \quad (94)$$

where $W_{L,R}$ is obtained by measuring the β particles in the opposite \hat{p}_e direction, while the nuclei are polarized in the $\uparrow(\downarrow)$ opposite \vec{j} direction. Similarly, χ_i^{0s} can also be obtained by measuring the decay asymmetry between the neutrino and electron in perpendicular directions.

The spatial directions of χ are defined in the laboratory frame and their absolute orientation depends on the orientation of Earth. It is therefore necessary to choose a standard absolute reference frame, for which the Sun-centered inertial reference frame is commonly chosen (Kostelecký and Russell, 2011). The movement of this reference frame can safely be ignored. The transformation of $\chi^{\mu\nu}$ in the laboratory frame to the Sun-centered frame, in which we denote $\chi^{\mu\nu}$ by $X^{\mu\nu}$, is (Noordmans, Wilschut, and Timmermans, 2013b)

$$\chi^{\mu\nu} = R^\mu_\rho R^\nu_\sigma X^{\rho\sigma}. \quad (95)$$

The transformation matrix is

$$R(\zeta, t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos \zeta \cos \Omega t & \cos \zeta \sin \Omega t & -\sin \zeta \\ 0 & -\sin \Omega t & \cos \Omega t & 0 \\ 0 & \sin \zeta \cos \Omega t & \sin \zeta \sin \Omega t & \cos \zeta \end{pmatrix}, \quad (96)$$

where ζ is the colatitude of the experiment and Ω is Earth's sidereal rotation frequency. In the laboratory frame, \hat{x} points in the north to south direction, \hat{y} points west to east, and \hat{z} is perpendicular to the Earth's surface. The coefficients χ_r^{0l} and $\tilde{\chi}_i^l$ can be transformed to X_r^{0l} and \tilde{X}_i^l , respectively. This transformation shows that the asymmetries A_F , A_{GT} , and A_J can oscillate with the rotational frequency of the Earth. These sidereal variations of the signal are a unique signature of Lorentz violation and can therefore be separated from other limits on BSM physics. A generic example of how sidereal oscillations can be observed is shown in Fig. 11, for $X_r^{0l} = 0.1$. This example also shows that if the β particles are detected parallel (\parallel) to the Earth's rotation axis, the asymmetry will have no sidereal dependence (thick line). The top curve shows the case where the β particles are detected in the east-west (\perp) direction. It has no offset because it is measured perpendicular to the Earth's rotation axis. The black line gives the asymmetry for β particles detected in the up-down ($\uparrow\downarrow$) direction perpendicular to the Earth's surface (\hat{z} direction in the lab frame). It shows a sidereal oscillation on a constant offset. Detection of the β particles perpendicular to the rotation axis is preferred, since an offset could be the result of systematic errors in the measurement.

Tensor contributions involving χ^{jk} lead to terms that may oscillate with twice the Earth's rotational frequency. Figure 12 illustrates three possible scenarios for an asymmetry that depends on $\chi^{lk} j^l \hat{p}_e^k$. Line (1) shows the modulations when the polarization is in the up-down direction, while the β particles are detected in the east-west direction. Line (2) shows the modulations in the same polarization direction, but when the β

⁶This formula corrects Eq. (38) in Noordmans, Wilschut, and Timmermans (2013b) (see also Appendix B).

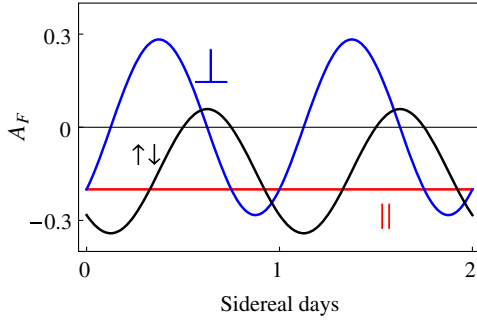


FIG. 11 (color online). Illustration of the oscillation of the asymmetry A_F in Eq. (91), for $X_r^{0l} = 0.1$ and $\zeta = 45^\circ$. Three different detection directions of the β particles are depicted. When β particles are detected parallel (\parallel) to the Earth's rotation axis there is no sidereal variation (thick line). The top curve shows the asymmetry when the β particles are detected in the east-west direction (\perp) and the black line shows when they are detected perpendicular to the Earth's surface ($\uparrow\downarrow$). Both show a sidereal variation, the latter with a constant offset.

particles are detected parallel to the Earth's rotation axis. It shows an oscillation with the period of the sidereal rotational frequency on top of a constant offset. Line (3) shows an oscillation with twice the period of the sidereal frequency. It arises when both the polarization and the β particles are detected in the east-west direction.

In allowed β decay, Lorentz violation was for the first time tested in polarized ^{20}Na (Müller *et al.*, 2013), by measuring the spin asymmetry A_J [Eq. (93)]. ^{20}Na first decays with a $\beta^+ 2^+ \rightarrow 2^+$ Gamow-Teller transition, followed by a γ decay of the daughter nucleus. The parity-odd β decay was used to determine the polarization P by measuring the β asymmetry (Müller *et al.*, 2013). The parity-even γ decay was used to measure the lifetime $\tau^{\uparrow(\downarrow)}$ and to determine the γ asymmetry

$$A_\gamma = \frac{\tau^\downarrow - \tau^\uparrow}{\tau^\downarrow + \tau^\uparrow} = PA\vec{\chi}_i \cdot \vec{j}, \quad (97)$$

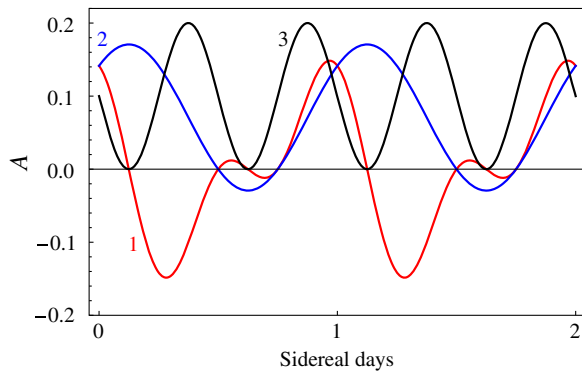


FIG. 12 (color online). Illustration of the possible sidereal variations of tensor Lorentz violation parametrized as $\chi_r^{lk} j^l \hat{p}_e^k$, with $X_r^{lk} = 0.1$. Line (1) shows the modulations when \vec{j} is in the \hat{z} (up-down) direction and \hat{p}_e in the \hat{y} (east-west) direction. Line (2) is for \vec{j} in the \hat{z} direction and the β particles detected parallel to the Earth's rotation axis. Line (3) shows the modulations when both \vec{j} and \hat{p}_e are in the east-west direction.

where the polarization direction is in the \vec{j} direction. To reduce systematic errors, the polarization direction is preferably in the \hat{y} (east-west) direction. The analysis of the setup in this direction places bounds of the order of $\mathcal{O}(10^{-3})$ (Sytema *et al.*, 2015).

Lorentz violation has also been searched for in polarized neutron decay (Bodek *et al.*, 2014). Two different asymmetries, that depend on the nuclear polarization and the β direction, were measured and are currently being analyzed. The asymmetries depend on combinations of $\vec{\chi}_i$ and $\vec{\chi}_r$ and preliminary bounds are $\mathcal{O}(10^{-2})$ (Bodek *et al.*, 2014). This setup probably also allows for a measurement of $A_{J\beta}$ defined in Eq. (94). Such a measurement would measure the so-far unconstrained coefficients χ_i^{0l} .

2. Forbidden β decay

“Forbidden” (slow) transitions are suppressed with respect to allowed transitions, because the lepton pair carries away angular momentum. Theoretically, the simplest of these transitions are the unique first-forbidden transitions ($\Delta J = 2$), since they depend on only one nuclear matrix element. Because Lorentz violation includes rotational violation, it also implies the violation of angular-momentum conservation. Forbidden β decays are then more sensitive to rotational invariance violation in the weak interaction. In the 1970s, two experiments were performed with this motivation. Newman and Wiesner (1976) searched for anisotropies in the angular distribution of β particles in first-forbidden ^{90}Y decay. Ullman (1978) searched for sidereal modulations of the count rates for first-forbidden ^{137}Cs β decay and second-forbidden ^{99}Tc β decay. The strongest bounds were found in the experiment by Newman and Wiesner (1976). In this experiment the β -decay distribution of ^{90}Y from a high-intensity source was measured in a rotating setup. Schematically, the setup is depicted in Fig. 13. The rotation of the setup allowed for the determination of three decay asymmetries

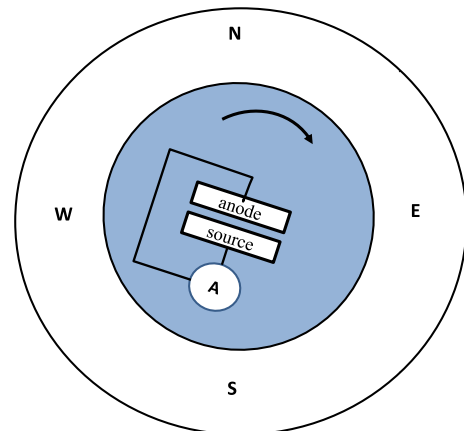


FIG. 13 (color online). Schematic setup of the rotating ^{90}Y experiment of Newman and Wiesner (1976).

$$\delta_{NS} = 2 \frac{W_N - W_S}{W_N + W_S}, \quad \delta_{EW} = 2 \frac{W_E - W_W}{W_E + W_W}, \quad (98)$$

and

$$\delta_{2\nu} = 2 \frac{W_N + W_S - W_E - W_W}{W_N + W_S + W_E + W_W}, \quad (99)$$

where N, S, E, W are north, south, east, and west and W is the decay rate measured by the β particles in that direction. These asymmetries were fitted with

$$\delta = a_0 + a_1 \sin(\Omega t + \phi_1) + a_2 \sin(2\Omega t + \phi_2) \quad (100)$$

to search for a sidereal time dependence and to reduce systematic errors. The extracted bounds on a_0, a_1 , and a_2 are $\mathcal{O}(10^{-8})$ (Newman and Wiesner, 1976). Noordmans, Wilschut, and Timmermans (2013a) reinterpreted the data from Newman and Wiesner (1976) and Ullman (1978), after extending the allowed β -decay framework to include higher-order terms in the multipole expansion, i.e., all possible forbidden decays. The modified W -boson propagator gives an unconventional contraction of the nucleon and lepton currents, such that angular momentum is no longer conserved. In the Lorentz-symmetric case, rotational invariance implies that $\Delta J \leq J_{\text{lep}}$, where ΔJ is the spin change of the nucleus and J_{lep} is the total angular momentum of the leptons. In contrast, when contracting with χ^{0l} , transitions with $\Delta J = J_{\text{lep}} + 1$ are possible, and when contracting with χ^{lk} also $\Delta J = J_{\text{lep}} + 2$ transitions are allowed. It is thus possible to have transitions in which the leptons carry away less angular momentum than in the Lorentz-symmetric case. Because the suppression of the forbidden decays is proportional to the angular momentum of the leptons, the Lorentz-violating terms are enhanced compared to the Lorentz-symmetric case.

For unique first-forbidden transitions (Noordmans, Wilschut, and Timmermans, 2013a)

$$\frac{dW}{d\Omega_e dE_e} \propto p_e^2 + p_\nu^2 + p_e^2 \frac{\alpha Z}{p_e R} \left[\frac{3}{10} \frac{p_e}{E_e} \left(\chi_r^{ij} \hat{p}^i \hat{p}^j - \frac{1}{3} \chi_r^{00} \right) - \frac{1}{2} \tilde{\chi}_i^l \hat{p}^l + \chi_r^{l0} \hat{p}^l \right], \quad (101)$$

where $\alpha Z/p_e R \simeq \mathcal{O}(10^1)$. Equation (101) shows that the Lorentz-violating contributions are enhanced. Higher-order forbidden decays do not have additional enhancement compared to the simpler first-forbidden transitions. Noordmans, Wilschut, and Timmermans (2013a) translated the bounds from Newman and Wiesner (1976) using Eq. (101). This led to strong limits on several combinations of $\chi^{\mu\nu}$. Assuming no cancellations between coefficients, this results in the limits (Noordmans, Wilschut, and Timmermans, 2013a)

$$\chi_r^{\mu\nu} = \begin{pmatrix} 10^{-6} & 10^{-7} & 10^{-7} & 10^{-8} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-7} & 10^{-6} & 10^{-6} & 10^{-6} \\ 10^{-8} & 10^{-6} & 10^{-6} & 10^{-6} \end{pmatrix} \quad \text{and} \quad \chi_i^{\mu\nu} = \begin{pmatrix} \times & - & - & - \\ - & \times & 10^{-8} & 10^{-7} \\ - & 10^{-8} & \times & 10^{-7} \\ - & 10^{-7} & 10^{-7} & \times \end{pmatrix}. \quad (102)$$

These are the strongest constraints on $\chi^{\mu\nu}$. The only coefficients not constrained by forbidden decays are χ_i^{0l} . These coefficients can be studied in allowed β decay by considering Eq. (94) or equivalent correlations. The bounds on χ were also translated into bounds on the SME parameters (Noordmans, Wilschut, and Timmermans, 2013a), providing strong direct bounds on the SME parameters $k_{\phi\phi}$ and $k_{\phi W}$ defined in Eq. (16).

3. Conclusion and outlook

We discussed the efforts to search for Lorentz violation in the weak interaction in forbidden and allowed β decays. The bounds from forbidden β decay are several orders of magnitude stronger than the current bounds in allowed β decay, due to the intense sources that were used (Newman and Wiesner, 1976; Ullman, 1978). In allowed β decay, Lorentz-violating effects are not enhanced and matching the statistical precision of forbidden β -decay experiments would require long-running experiments with high-intensity sources. An interesting alternative lies in orbital electron capture, where it is possible to use such high-intensity sources (Vos, Wilschut, and Timmermans, 2015b).

Allowed β decay offers various correlations in which Lorentz violation could be probed. Observables can be chosen such that they give direct constraints on χ compared to the combination of coefficients constrained by forbidden decays. Two relatively simple experiments that probe the β asymmetry in Fermi and Gamow-Teller decays, A_F and A_{GT} , respectively, give direct bounds on χ_r^{0l} and $\tilde{\chi}_i$. These asymmetries could be studied parallel to the efforts to measure the β -spectrum shape discussed in Sec. IV.D (Vos, Wilschut, and Timmermans, 2015a). Another interesting possibility is to exploit the γ^2 enhancement of decay asymmetries by considering fast-moving nuclei (Altschul, 2013; Vos *et al.*, 2014; Vos, Wilschut, and Timmermans, 2015a). The total decay rate in the rest frame of the nucleus is proportional to χ_r^{00} [see Eqs. (86) and (87)]. For a fast-moving nucleus, the expression can be related to the Sun-centered frame with a boost. If the nucleus is moving ultrarelativistically in the \hat{v} direction,

$$\chi_r^{00} = \gamma_r^2 (X_r^{TT} + 2X_r^{TL} \hat{v}^L + X_r^{LK} \hat{v}^L \hat{v}^K), \quad (103)$$

where γ_r is the Lorentz-boost factor and T, L , and K are coordinates in the Sun-centered reference frame. This relation was, for example, used to extract bounds of $\mathcal{O}(10^{-4})$ from pion decay (Altschul, 2013). For allowed β decay, β -beam

facilities, currently considered for producing neutrino beams (Lindroos and Mezzetto, 2010), could be exploited.

So far the coefficients χ_i^{0l} remain unconstrained. In Fermi decays, this coefficient could be measured by considering the correlation $\chi_i^{0l}(\vec{p}_e \times \vec{p}_\nu)^l$. The coefficients can also be constrained by measuring the polarized β asymmetry $A_{J\beta}$ in Eq. (94). Such an asymmetry could probably be explored in the neutron-decay measurement pursued by Bodek *et al.* (2014).

B. Neutrino sector

A different possibility to study Lorentz violation in β decay lies in the neutrino sector of the SME (Kostelecký and Mewes, 2004, 2012). Most interesting for β decay are the modified versions of a^{LV} and c^{LV} defined in Eq. (15).

Unlike the gauge sector, the neutrino sector has been studied extensively in several experiments. Strong bounds exist from neutrino oscillations and time-of-flight measurements (Kostelecký and Russell, 2011). However, there are four operators that do not show up in oscillations and have no effect on the neutrino group velocity. These operators are called “countersshaded” (Kostelecký and Tasson, 2009). Recently, Díaz, Kostelecký, and Lehnert (2013) showed that β decay has a unique sensitivity to these operators. The four countersshaded coefficients are denoted by $a_{\text{of}}^{(3)}$. The operators are dimension 3 and CPT odd. These coefficients modify the neutrino dispersion relation and the available phase space of the neutrino, which affects β decay in two ways, in the β end point and in the correlation coefficients.

1. End point in β decay

The β -spectrum end point is very sensitive to the neutrino phase space and to the neutrino mass (see also Sec. IV.C). Independent of the neutrino mass, the countersshaded neutrino coefficients also shift the end point, as can be seen from the modified decay rate (Díaz, Kostelecký, and Lehnert, 2013; Díaz, 2014)

$$\frac{dW}{dT} \sim (\Delta T + \delta T_{LV})^2 - \frac{1}{2}m_\nu^2, \quad (104)$$

where $\Delta T = T_0 - T_e$, $T_e = E_e - m_e$ is the electron kinetic energy, and T_0 is the end-point energy for $m_\nu = 0$. δT_{LV} is the Lorentz-violating modification, which depends on sidereal time. Independent of the neutrino mass, a bound on the countersshaded coefficients can be set by using the available data of the Troitsk (Kraus *et al.*, 2005) and Mainz (Aseev *et al.*, 2011) experiments; see Díaz, Kostelecký, and Lehnert (2013). Since these experiments collected data over a long period of time, all the oscillations average out and only the time-averaged Lorentz-violating coefficients can be constrained. Therefore, only two of the four countersshaded coefficients could be bounded. Conservatively, the analysis of Díaz, Kostelecký, and Lehnert (2013) gives bounds of order $\mathcal{O}(10^{-8})$ GeV. These limits improve and complement previous limits. A dedicated analysis of the data of the Troitsk, Mainz, or the expected KATRIN (Otten and Weinheimer, 2008) experiments could improve these results. If the data analysis also takes into account the sidereal time, bounds on all the countersshaded coefficients could be set.

2. Correlation coefficients

The Lorentz-violating neutrino coefficients of Eq. (15) also modify the neutrino spinor solutions. Near the end point, this modification can be neglected because the phase space dominates. However, the derivation of the complete modified decay rate requires both the modified spinors and the phase-space modification. The modified neutrino phase space is $d^3\vec{p}_\nu \simeq (E_\nu^2 - 2E_\nu a_{\text{of}}^{(3)})dE_\nu d\Omega_\nu$. The modification of the spinors requires the replacement of \vec{p}_ν by $\tilde{\vec{p}}_\nu = (\vec{p}_\nu + \vec{a}_{\text{of}}^{(3)} - \hat{a}_{\text{of}}^{(3)}\hat{p}_\nu)$, where $\hat{a}_{\text{of}}^{(3)}$ is the isotropic component. The modified neutron-decay rate is

$$\begin{aligned} \frac{dW}{dE_e d\Omega_\nu dT} &\simeq F(Z, E) |\vec{p}_e| E_e (E_\nu^2 + 2E_\nu \delta T_{LV}) \\ &\times \left(1 + a\vec{\beta} \cdot \vec{p}_\nu + A \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p}_e}{E_e} + B \frac{\langle \vec{J} \rangle}{J} \cdot \frac{\vec{p}_\nu}{E_\nu} \right). \end{aligned} \quad (105)$$

The neutrino coefficients modify the decay rate in a similar way as χ does, since there are now additional correlations between \vec{J} and \vec{p}_e and $a_{\text{of}}^{(3)}$.

The countersshaded coefficients could, for example, affect the β - ν correlation. The β - ν correlation can be measured as an asymmetry, defined by

$$\tilde{a} = \frac{N_+ - N_-}{N_+ + N_-}, \quad (106)$$

where N_+ (N_-) is the number of decays in which the neutrino and electron are emitted (anti)parallel. The Lorentz-violating neutrino coefficients modify this correlation coefficient to (Díaz, 2014)

$$\tilde{a} = a|\vec{\beta}| + \sqrt{\frac{3}{\pi}} \frac{(a\beta^2 + a|\vec{\beta}|)}{E_\nu} (a_{\text{of}}^{(3)})_{10}^{\text{lab}}, \quad (107)$$

where the coefficients should be transformed to the Sun-centered frame and would depend on the sidereal frequency of the Earth.

No experiment has searched for these variations, but Díaz, Kostelecký, and Lehnert (2013) estimated that a 0.1% measurement of a would limit the countersshaded coefficients at the level of 10^{-8} GeV. Similar, for a 0.1% measurement of the correlation coefficient B , the limits are estimated at $\mathcal{O}(10^{-6})$ GeV. A dedicated experiment measuring either a or B would thus provide interesting new bounds on Lorentz-violating parameters in the neutrino sector. Note that χ and $a_{\text{of}}^{(3)}$ have a similar influence on the decay rate. In a dedicated experiment both coefficients might influence the asymmetry. A measurement of Eq. (106) might also be sensitive to χ_r^{0l} and $\tilde{\chi}_i$, depending on the experimental setup.

C. Conclusion

To summarize, β decay offers a unique way to study Lorentz violation in both the gauge and neutrino sectors. The large variety of correlations allows for direct measurements of

different components of χ , while in the neutrino sector β decay allows for the study of countershaded coefficients.

In the gauge sector, strong bounds on the order of 10^{-6} – 10^{-8} exist from forbidden β -decay experiments. Unconstrained are the coefficients χ_i^{0l} , which can be accessed in β decay by considering the interaction of χ with two observables [Eq. (94)]. Improving the existing bounds requires high statistics and precise knowledge of the systematic uncertainties. Beneficial for this would be to exploit the γ_r^2 enhancement of boosted β decay or to consider electron capture. The real and imaginary parts of χ can be constrained by measuring the asymmetries in Eqs. (91) and (92), respectively. Such an effort could be combined with measurements of the Fierz-interference term.

Further, we discussed the possibilities to improve constraints on Lorentz violation in the countershaded neutrino sector. In that sector no dedicated experiment has been performed so far, but using available data from tritium gives bounds of the order of 10^{-8} GeV. The parameters not constrained so far could be bound in β -decay correlation experiments. Lorentz violation gives a unique signal compared to other BSM physics when searched for in a dedicated experiment. Estimates for 0.1% measurements of the coefficients a and B gives a constraint on Lorentz violation of 10^{-8} GeV, which shows the potential for these future experiments.

VII. SUMMARY AND DISCUSSION

In this review we addressed the current status and role of nuclear and neutron β decay in the search for physics beyond the SM. In these searches, the statistical precision is becoming increasingly important. However, systematic errors, despite improved detection methods, and higher-order corrections such as FSI, still appear to be the main limits. In the meantime, thanks to the evolution of EFT methods, constraints obtained in other fields weigh in, establishing bounds on the scalar and tensor contributions. This is illustrated in Figs. 6 and 7, where measurements at the LHC (Sec. IV.B) and limits from the neutrino mass (Sec. IV.C) give constraints that outperformed the β -correlation measurements in the right-handed sector. This is quantified in Table IV.

The study of fundamental aspects of β decay will be most fruitful in the study of left-handed scalar (Sec. IV.A.1) and tensor currents (Sec. IV.A.2), as these appear linearly in most observables via the Fierz-interference term. Fortunately, these interactions can be studied in parallel to precision studies of SM parameters (Sec. III.B). For example, extracting the CKM matrix element V_{ud} from superallowed Fermi transitions has, as a by-product, the most strict limit on left-handed scalar interactions. Lacking still is a similar limit on tensor contributions. An interesting option to obtain such a bound could come from measuring the detailed shape of the β spectrum in Gamow-Teller transitions. Also the potential of mirror transitions, both for obtaining tensor limits and for obtaining a value for V_{ud} independent of the superallowed Fermi transitions, has been recognized. In Table V we indicate the precision required to impose new bounds on left- and right-handed scalar and tensor currents. Measuring the Fierz-interference term in β decay remains competitive in determining bounds on left-handed

coupling constants. In contrast, Table V shows that, for right-handed couplings, the limits from the LHC and the limits derived from the neutrino mass are by far superior to the best bounds derived from the $\beta\nu$ -correlation a , and future experiments in β decay are unlikely to reach this precision.

Concerning the most fundamental measurement of T violation, we discussed in Sec. V the strong bounds on the triple-correlation coefficients D and R derived from the limits on permanent EDMs. These bounds are summarized in Table VII. Not only are the bounds from EDMs several orders of magnitude stronger than those of β decay, but the EDM limits also have a large potential to improve faster than those from β decay. One reason is that EDMs can be measured in stable or long-lived particles, but also because of the widely perceived urgency for improved limits in this sector.

A new twist to the discussion of symmetry violations in β decay has been added, since β decay also offers an interesting sensitivity to Lorentz violation in the weak interaction. In Sec. VI, we reviewed these limits for the first time. Because the discrete symmetries C , P , and T are each violated in the weak interaction, this interaction is a promising portal to search for new physics when considering CPT violation and thus Lorentz violation. The familiar β -decay correlations are now extended to include correlations between spin and momentum and a Lorentz-violating background tensor. Consequently, spin and momentum appear to have preferred directions in absolute space, resulting in unique signals that can be distinguished from other BSM searches.

In weak decays Lorentz violation has been parametrized with the complex tensor χ . The bounds on most components of this tensor are of the order of 10^{-6} to 10^{-8} (Sec. VI.A.2). Fine-tuning between the tensor components allows one to weaken these bounds. Relatively simple new experiments can improve these bounds using very strong sources, also removing the possibility of fine-tuning. Obtaining sufficient high counting statistics is the main challenge. The searches for Lorentz violation can be expanded in a parallel effort with the more traditional searches. Alternatively, one can study β decay in flight, exploiting the γ_r^2 enhancement. In this respect there may be as yet unexplored possibilities related to semileptonic decays in high-energy physics. Because this field of research is relatively unexplored, both experimentally and theoretically, the best approach may still emerge.

Improvements in theory and experimental techniques, as well as new radioactive-beam facilities, provide new possibilities to study fundamental aspects of β decay, both in the search for exotic interactions and in the search for Lorentz violation. These studies should be done by considering also the other searches in high-energy physics and precision physics at low energies. Nuclear and neutron β decay will remain an important topic on the research agenda.

ACKNOWLEDGMENTS

We are grateful to our colleagues J. Behr, K. Bodek, W. Dekens, J. de Vries, M. González-Alonso, O. Naviliat-Cuncic, J. Noordmans, G. Onderwater, N. Severijns, F. Wauters, and A. Young for fruitful discussions and updates on the experimental progress. We especially thank the organizers of the 33rd Solvay Workshop on Beta Decay Weak Interaction

Studies in the Era of the LHC (Brussels, 3–5 September 2014). This research was supported by the Dutch Stichting voor Fundamenteel Onderzoek der Materie (FOM) under Programmes 104 and 114.

APPENDIX A: DECAY COEFFICIENTS

Our formalism can be linked to the original work of Lee and Yang (1956) and Jackson, Treiman, and Wyld (1957a), where⁷

$$\begin{aligned}\mathcal{L}_{\text{eff}} = & \bar{p}n\bar{e}(C_S - C'_S\gamma_5)\nu_e \\ & + \bar{p}\gamma^\mu n\bar{e}\gamma_\mu(C_V - C'_V\gamma_5)\nu_e \\ & + \bar{p}\gamma^\mu\gamma_5 n\bar{e}\gamma_\mu(C'_A - C_A\gamma_5)\nu_e \\ & + \frac{1}{2}\bar{p}\sigma^{\mu\nu} n\bar{e}\sigma_{\mu\nu}(C_T - C'_T\gamma_5)\nu_e.\end{aligned}\quad (\text{A1})$$

This notation can be related to our couplings in Eq. (11) by using the normalized couplings

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud} \bar{C}_i, \quad (\text{A2})$$

and

$$\begin{aligned}\bar{C}_V &= g_V(a_L + a_R), \\ \bar{C}'_V &= g_V(a_L - a_R), \\ \bar{C}_A &= -|g_A|(a'_L + a'_R), \\ \bar{C}'_A &= -|g_A|(a'_L - a'_R), \\ \bar{C}_S &= g_S(A_L + A_R), \\ \bar{C}'_S &= g_S(A_L - A_R), \\ \bar{C}_T &= 2g_T(\alpha_L + \alpha_R), \\ \bar{C}'_T &= 2g_T(\alpha_L - \alpha_R).\end{aligned}\quad (\text{A3})$$

For simplicity we have defined

$$\begin{aligned}a_L &\equiv a_{LL} + a_{LR}, \\ a_R &\equiv a_{RR} + a_{RL}, \\ a'_L &\equiv a_{LL} - a_{LR}, \\ a'_R &\equiv a_{RR} - a_{RL}, \\ A_L &\equiv A_{LR} + A_{LL}, \\ A_R &\equiv A_{RL} + A_{RR}.\end{aligned}\quad (\text{A4})$$

We write α_L and α_R as in Eq. (11), because $\sigma_{\mu\nu}\gamma_5 = (i/2)\epsilon_{\mu\nu\alpha\beta}\sigma^{\alpha\beta}$. The coefficients $a_{\epsilon\delta}$, $A_{\epsilon\delta}$, and α_ϵ are related to the ϵ coefficients in Cirigliano, González-Alonso, and Graesser (2013) and Naviliat-Cuncic and González-Alonso (2013) by using

$$\begin{aligned}\{a_{LL}, a_{LR}, a_{RL}, a_{RR}, A_{LL} + A_{LR}, A_{RR} + A_{RL}, \alpha_L, \alpha_R\} \\ = \{1 + \epsilon_L, \epsilon_R, \tilde{\epsilon}_L, \tilde{\epsilon}_R, \epsilon_S, \tilde{\epsilon}_S, 2\epsilon_T, 2\tilde{\epsilon}_T\}.\end{aligned}\quad (\text{A5})$$

A full list of correlation coefficients in allowed β decay including Coulomb corrections is given in Jackson, Treiman, and Wyld (1957a, 1957b). Here we give the most important decay coefficients in terms of couplings defined in Eq. (9). We emphasize that only b , B , and N depend linearly on scalar and tensor couplings. We define $\lambda = |g_A|/g_V > 0$ and neglect Coulomb interactions. The spin factors are

$$\lambda_{J'J} = \begin{cases} 1, & J \rightarrow J' = J - 1, \\ \frac{1}{J+1}, & J \rightarrow J' = J, \\ \frac{-J}{J+1}, & J \rightarrow J' = J + 1, \end{cases}\quad (\text{A6})$$

and

$$\Lambda_{J'J} = \begin{cases} 1, & J \rightarrow J' = J - 1, \\ \frac{-(2J-1)}{J+1}, & J \rightarrow J' = J, \\ \frac{J(2J-1)}{(J+1)(2J+3)}, & J \rightarrow J' = J + 1, \end{cases}\quad (\text{A7})$$

where J and J' are the spin of the initial and final nucleus, respectively. In the following equations, M_F and M_{GT} are the Fermi and Gamow-Teller matrix elements, the upper (lower) sign refers to β^- (β^+) decay, and $\gamma = \sqrt{1 - \alpha^2 Z^2}$, with Z the atomic number of the daughter nucleus and α the fine-structure constant.

Because of our normalization of the couplings in Eq. (11) we define

$$\bar{\xi} \equiv \frac{G_F^2 V_{ud}^2}{2} \xi, \quad (\text{A8})$$

with

$$\xi = 2g_V^2 |M_F|^2 \left\{ |a_L|^2 + |a_R|^2 + \frac{g_S^2}{g_V^2} (|A_L|^2 + |A_R|^2) \right\} + 2g_V^2 \lambda^2 |M_{GT}|^2 \left\{ |a'_L|^2 + |a'_R|^2 + 4 \frac{g_T^2}{g_A^2} (|\alpha_L|^2 + |\alpha_R|^2) \right\}. \quad (\text{A9})$$

Neglecting Coulomb interactions, the decay coefficients are (Jackson, Treiman, and Wyld, 1957a, 1957b)

$$a\xi = 2g_V^2 |M_F|^2 \left\{ |a_L|^2 + |a_R|^2 - \frac{g_S^2}{g_V^2} (|A_L|^2 + |A_R|^2) \right\} + 2g_V^2 \lambda^2 \frac{|M_{GT}|^2}{3} \left\{ -|a'_L|^2 - |a'_R|^2 + 4 \frac{g_T^2}{g_A^2} (|\alpha_L|^2 + |\alpha_R|^2) \right\}, \quad (\text{A10})$$

⁷Using our definition of γ_5 and neglecting pseudoscalar couplings.

$$b\xi = \pm 2g_V^2\gamma \left\{ 2|M_F|^2 \frac{g_S}{g_V} [\text{Re}(A_L a_L^*) + \text{Re}(A_R a_R^*)] - 4 \frac{g_T}{|g_A|} \lambda^2 |M_{GT}|^2 [\text{Re}(\alpha_L a_L^*) + \text{Re}(\alpha_R a_R^*)] \right\}, \quad (\text{A11})$$

$$c\xi = 2g_V^2\lambda^2 \Lambda_{J'J} |M_{GT}|^2 \left\{ -|a'_L|^2 - |a'_R|^2 + 4 \frac{g_T^2}{g_A^2} [|\alpha_L|^2 + |\alpha_R|^2] \right\}, \quad (\text{A12})$$

$$A\xi = \pm 2g_V^2\lambda^2 |M_{GT}|^2 \lambda_{J'J} \left\{ 4 \frac{g_T^2}{g_A^2} [|\alpha_L|^2 - |\alpha_R|^2] - [|a'_L|^2 - |a'_R|^2] \right\} + 2g_V^2\lambda\delta_{J'J} |M_F| |M_{GT}| \sqrt{\frac{J}{J+1}} \left\{ 4 \frac{g_T g_S}{|g_A| g_V} [\text{Re}(A_L a_L^*) - \text{Re}(A_R a_R^*)] \right. \\ \left. + 2[|a_{LL}|^2 - |a_{LR}|^2 - |a_{RR}|^2 + |a_{RL}|^2] \right\}, \quad (\text{A13})$$

$$B\xi = 2g_V^2\lambda^2 |M_{GT}|^2 \lambda_{J'J} \left\{ \frac{-4g_T}{|g_A|} \frac{m_e \gamma}{E_e} [\text{Re}(\alpha_L a_L^*) - \text{Re}(\alpha_R a_R^*)] \pm \frac{4g_T^2}{g_A^2} [|\alpha_L|^2 - |\alpha_R|^2] \pm [|a'_L|^2 - |a'_R|^2] \right\} \\ - 2g_V^2\lambda\delta_{J'J} |M_F| |M_{GT}| \sqrt{\frac{J}{J+1}} \left\{ \frac{4g_T g_S}{g_V |g_A|} [\text{Re}(A_L a_L^*) - \text{Re}(A_R a_R^*)] - 2[|a_{LL}|^2 - |a_{LR}|^2 - |a_{RR}|^2 + |a_{RL}|^2] \right. \\ \left. \pm \frac{m_e \gamma}{E_e} \left(-\frac{2g_S}{g_V} [\text{Re}(A_L a_L^*) - \text{Re}(A_R a_R^*)] + \frac{4g_T}{|g_A|} [\text{Re}(a_L a_L^*) - \text{Re}(a_R a_R^*)] \right) \right\}, \quad (\text{A14})$$

$$D\xi = 2g_V^2\lambda\delta_{J'J} |M_F| |M_{GT}| \sqrt{\frac{J}{J+1}} \left\{ \frac{4g_T g_S}{g_V |g_A|} [\text{Im}(A_L a_L^*) + \text{Im}(A_R a_R^*)] + 2[\text{Im}(a_L a_L^*) + \text{Im}(a_R a_R^*)] \right\}, \quad (\text{A15})$$

$$R\xi = \pm 2g_V^2\lambda^2 |M_{GT}|^2 \lambda_{J'J} \frac{-4g_T}{|g_A|} [\text{Im}(\alpha_L a_L^*) - \text{Im}(\alpha_R a_R^*)] + 2g_V^2\lambda\delta_{J'J} |M_F| |M_{GT}| \sqrt{\frac{J}{J+1}} \left\{ -2[\text{Im}(A_L a_L^*) - \text{Im}(A_R a_R^*)] \right. \\ \left. - \frac{4g_T}{|g_A|} [\text{Im}(a_L a_L^*) - \text{Im}(a_R a_R^*)] \right\}, \quad (\text{A16})$$

and

$$N\xi = 2g_V^2\lambda^2 |M_{GT}|^2 \lambda_{J'J} \left\{ \frac{m_e \gamma}{E_e} [|a'_L|^2 + |a'_R|^2 + 4 \frac{g_T^2}{g_A^2} [|\alpha_L|^2 + |\alpha_R|^2]] \mp \frac{4g_T^2}{g_A^2} [\text{Re}(\alpha_L a_L^*) + \text{Re}(\alpha_R a_R^*)] \right\} \\ + 2g_V^2\lambda\delta_{J'J} |M_F| |M_{GT}| \sqrt{\frac{J}{J+1}} \left\{ -\frac{2g_S}{g_V} [\text{Re}(A_L a_L^*) + \text{Re}(A_R a_R^*)] + \frac{4g_T}{|g_A|} [\text{Re}(a_L a_L^*) + \text{Re}(a_R a_R^*)] \right. \\ \left. \pm \frac{\gamma m_e}{E_e} \left(\frac{4g_T g_S}{g_V |g_A|} [\text{Re}(A_L a_L^*) + \text{Re}(A_R a_R^*)] - 2[|a_{LL}|^2 - |a_{LR}|^2 + |a_{RR}|^2 - |a_{RL}|^2] \right) \right\}. \quad (\text{A17})$$

The longitudinal electron polarization is (Jackson, Treiman, and Wyld, 1957a, 1957b)

$$P = \frac{G \frac{v_e}{c}}{1 + b \langle \frac{m_e}{E_e} \rangle}, \quad (\text{A18})$$

with

$$G\xi = \pm 2|M_F|^2 g_V^2 \left\{ \frac{g_S^2}{g_V^2} [|A_L|^2 - |A_R|^2] - |a_L|^2 + |a_R|^2 \right\} \pm 2|M_{GT}|^2 g_V^2 \lambda^2 \left\{ \frac{4g_T^2}{g_A^2} [|\alpha_L|^2 - |\alpha_R|^2] - [|a'_L|^2 - |a'_R|^2] \right\}. \quad (\text{A19})$$

The neutron lifetime [Eq. (40)] depends on V_{ud} , which is extracted from the $0^+ \rightarrow 0^+$ superallowed Fermi decays. However, the extracted value of V_{ud} might also depend on new physics. Taking into account this possibility,

$$\tau_n = K \frac{1 - 2 \frac{g_S}{g_V} A_L \gamma \langle \frac{m_e}{E_e} \rangle^{0^+ \rightarrow 0^+} + \frac{g_S^2}{g_V^2} A_L^2 + \frac{g_S^2}{g_V^2} A_R^2}{1 + \frac{g_S^2}{g_V^2} A_L^2 + \frac{g_S^2}{g_V^2} A_R^2 + 3\lambda^2 (1 + 4 \frac{g_T^2}{g_A^2} \alpha_L^2 + 4 \frac{g_T^2}{g_A^2} \alpha_R^2) + \gamma \langle \frac{m_e}{E_e} \rangle (2 \frac{g_S}{g_V} A_L - 12\lambda^2 \frac{g_T}{|g_A|} \alpha_L)}, \quad (\text{A20})$$

where $\langle m_e/E_e \rangle^{0^+ \rightarrow 0^+}$ is the inverse average energy of the superallowed decays, calculated by Pattie, Hickerson, and Young (2013). The constant K is (Pattie, Hickerson, and Young, 2013)

$$K \equiv \frac{2\pi^3}{m_e^5 f_n (1 + \Delta_{RC}) G_F^2 V_{ud}^2} = (1.9342 \pm 0.002) \times 10^{-4}, \quad (\text{A21})$$

where $f_n = 1.6887(2)$ is the statistical rate function (Towner and Hardy, 2010) and Δ_{RC} are the SM electroweak corrections (Czarnecki, Marciano, and Sirlin, 2004).

The SM expressions can be obtained by setting $a_{LL} = 1$ and neglecting all other couplings. Defining $\rho \equiv |g_A| M_{GT} / g_V M_F$, the remaining SM expressions are

$$a_{SM} = \frac{1 - \rho^2/3}{1 + \rho^2}, \quad (\text{A22a})$$

$$A_{SM} = \frac{\mp \lambda_{J'J} \rho^2 + 2\delta_{J'J} \sqrt{J/(J+1)} \rho}{1 + \rho^2}, \quad (\text{A22b})$$

$$B_{SM} = \frac{\pm \lambda_{J'J} \rho^2 + 2\delta_{J'J} \sqrt{J/(J+1)} \rho}{1 + \rho^2}, \quad (\text{A22c})$$

$$G_{SM} = \mp 1, \quad (\text{A22d})$$

while all other coefficients vanish. For neutron decay, $\rho = \sqrt{3}|g_A|$ and $J = J' = 1/2$.

1. Linear terms in B

The B coefficients contains terms linear in exotic couplings. Neglecting quadratic couplings, we can write

$$B\xi = \pm \lambda_{J'J} \rho^2 + 2\rho \delta_{J'J} \sqrt{J/(J+1)} + \left\langle \frac{m_e \gamma}{E_e} \right\rangle b_B \xi, \quad (\text{A23})$$

where

$$b_B \xi = -\rho^2 \lambda_{J'J} \frac{4g_T}{|g_A|} \text{Re} \alpha_L \mp \delta_{J'J} \rho \sqrt{\frac{J}{J+1}} \left[-\frac{2g_S}{g_V} \text{Re} A_L + \frac{4g_T}{|g_A|} \text{Re} \alpha_L \right]. \quad (\text{A24})$$

Most B measurements measure

$$\tilde{B} = \frac{B_{SM} + b_B \gamma \langle \frac{m_e}{E_e} \rangle}{1 + b \langle \frac{m_e}{E_e} \rangle}. \quad (\text{A25})$$

For pure Gamow-Teller transitions, with $\rho \rightarrow \infty$, $\tilde{B}_{GT} = \pm \lambda_{J'J}$, and the linear dependence cancels. For neutron decay and assuming real couplings, $B_{SM} \simeq 1$ and

$$\begin{aligned} \tilde{B} &\simeq B_{SM} + \left\langle \frac{m_e}{E_e} \right\rangle (\gamma b_B - b B_{SM}) \\ &\simeq \frac{2(\lambda + \lambda^2)}{1 + 3\lambda^2} + \left\langle \frac{m_e \gamma}{E_e} \right\rangle \frac{-\lambda - 2\lambda^2 + 3\lambda^3}{(1 + 3\lambda^2)^2} \left[2 \frac{g_S}{g_V} A_L + 4 \frac{g_T}{|g_A|} \alpha_L \right] \\ &\simeq 1 + \left[0.1 \frac{g_S}{g_V} A_L + 0.2 \frac{g_T}{|g_A|} \alpha_L \right] \left\langle \frac{m_e \gamma}{E_e} \right\rangle. \end{aligned} \quad (\text{A26})$$

For comparison, for neutron decay, the Fierz-interference term is

$$\begin{aligned} b_{\text{neutron}} &= \frac{2 \frac{g_S}{g_V} A_L - 12\lambda^2 \frac{g_T}{|g_A|} \alpha_L}{1 + 3\lambda^2} \\ &\simeq 0.35 \frac{g_S}{g_V} A_L - 3.3 \frac{g_T}{|g_A|} \alpha_L. \end{aligned} \quad (\text{A27})$$

For the measured \tilde{A} coefficient in neutron decay, with $A_{SM} \simeq -0.11$,

$$\tilde{A}_{\text{neutron}} = A_{SM} \mp A_{SM} \frac{m_e \gamma}{E_e} \left(0.35 \frac{g_S}{g_V} A_L - 3.3 \frac{g_T}{|g_A|} \alpha_L \right). \quad (\text{A28})$$

So for neutron decay, B actually has a reduced sensitivity to scalar and in particular tensor terms compared to, for example, A .

APPENDIX B: LORENTZ VIOLATION

The Lorentz-violating β -decay rate including Coulomb corrections and electron spin, to first order in $\chi^{\mu\nu}$, is (Noordmans, Wilschut, and Timmermans, 2013b)

$$\begin{aligned} dW &= \frac{1}{(2\pi)^5} E_e p_e (E_0 - E_e)^2 F(\pm Z, E_e) \bar{\xi} dE_e d\Omega_e d\Omega_\nu \left\{ \left(1 \mp \frac{\vec{p}_e \cdot \hat{s}_e}{E_e} \right) \left[\frac{1}{2} \left(1 + B \frac{\vec{p}_\nu \cdot \langle \vec{J} \rangle}{J E_\nu} \right) + t + \frac{\vec{w}_1 \cdot \vec{p}_\nu}{E_\nu} + \vec{w}_2 \cdot \frac{\langle \vec{J} \rangle}{J} \right] \right. \\ &\quad + T_1^{km} j^k j^m + T_2^{kj} \frac{\langle J^k \rangle p_\nu^j}{J E_\nu} + \frac{S_1^{kmj} j^k j^m p_\nu^j}{E_\nu} \left. \right] + \left(\left(1 \mp \frac{(E_e - \gamma m_e)(\vec{p}_e \cdot \hat{\sigma}_e)}{E_e^2 - m_e^2} \right) \frac{p_e^l}{E_e} \mp \frac{\gamma m_e}{E_e} \hat{\sigma}_e^l \mp \frac{m_e}{E_e} \sqrt{1 - \gamma^2} (\hat{p}_e \times \hat{\sigma}_e)^l \right) \\ &\quad \times \left[\frac{1}{2} A \frac{\langle J^k \rangle}{J} - \frac{3}{2} c' \frac{\vec{p}_\nu \cdot \vec{j}}{E_\nu} j^l + \frac{1}{2} (a + c') \frac{p_\nu^l}{E_\nu} + w_3^l + \frac{T_3^{lj} p_\nu^j}{E_\nu} + T_4^{lk} \frac{\langle J^k \rangle}{J} + S_2^{lmk} j^m j^k + \frac{S_3^{lmj} \langle J^m \rangle p_\nu^j}{J E_\nu} + \frac{R^{lmkj} j^m j^k p_\nu^j}{E_\nu} \right] \left. \right\}, \end{aligned} \quad (\text{B1})$$

where $\gamma = \sqrt{1 - a^2 Z^2}$. The Lorentz-violating constants are⁸

⁸Note the sign error in w_3^l in Noordmans, Wilschut, and Timmermans (2013b).

$$\begin{aligned}
t &= (a - \frac{1}{2}c')\chi_r^{00}, & w_1^j &= -x\chi_r^{0j} + \check{g}(\chi_r^{j0} - \tilde{\chi}_i^j), & w_2^k &= \check{K}(\chi_r^{k0} - \chi_r^{0k}) - \check{L}\tilde{\chi}_i^k, & w_3^l &= -x\chi_r^{0l} + \check{g}(\chi_r^{l0} + \tilde{\chi}_i^l), \\
T_1^{km} &= \frac{3}{2}c'\chi_r^{km}, & T_2^{kj} &= \frac{1}{2}A\chi_r^{00}\delta^{jk} + \check{L}(\chi_r^{jk} + \chi_i^{s0}e^{sjk}) - \check{K}(\chi_r^{kj} + \chi_i^{0s}e^{sjk}), \\
T_3^{lj} &= (x + \check{g})\chi_r^{00}\delta^{lj} - (x\chi_i^{0s} + \check{g}\chi_i^{s0})e^{sjl} - \check{g}(\chi_r^{jl} + \chi_r^{lj}), \\
T_4^{lk} &= \frac{1}{2}B\chi_r^{00}\delta^{lk} - \check{L}(\chi_r^{lk} - \chi_i^{s0}e^{ksl}) - \check{K}(\chi_r^{kl} - \chi_i^{0s}e^{ksl}), & S_1^{kmj} &= -\frac{3}{2}c'(\chi_r^{k0}\delta^{mj} - \chi_i^{ms}e^{sjk}), & S_2^{lmk} &= -\frac{3}{2}c'(\chi_r^{m0}\delta^{kl} + \chi_i^{ms}e^{slk}), \\
S_3^{lmj} &= \check{L}(\chi_r^{l0}\delta^{jm} - \chi_i^{sl}e^{sjm} - \chi_r^{j0}\delta^{ml} + \tilde{\chi}_i^m\delta^{jl} - \chi_i^{sj}e^{lms}) + \check{K}(\chi_i^{00}e^{ljm} - \chi_r^{0l}\delta^{jm} - \chi_r^{0j}\delta^{ml} + (\chi_r^{0m} + \chi_r^{m0})\delta^{jl} - \chi_i^{ms}e^{sjl}), \\
R^{lmkj} &= \frac{3}{2}c'(\chi_i^{m0}e^{lkj} - \chi_r^{mk}\delta^{lj} + \chi_r^{ml}\delta^{kj} + \chi_r^{mj}\delta^{kl}),
\end{aligned} \tag{B2}$$

where r and i denote the real and imaginary parts of $\chi^{\mu\nu}$, respectively, $\tilde{\chi}^l = \epsilon^{lmk}\chi^{mk}$, and p^l denotes the electron momentum in the l direction. a , A , B , and $\bar{\xi}$ are the standard β -decay coefficients, given in Eq. (A22); the other coefficients are

$$\begin{aligned}
x &= \frac{1}{1 + \rho^2}, & y &= \frac{-\rho}{1 + \rho^2}, \\
c' &= (1 - x)\bar{\Lambda}_{JJ'}, \\
\check{g} &= \frac{1}{3}(1 - x)\left(1 + \frac{3}{2}\bar{\Lambda}_{JJ'}\right), \\
\check{K} &= -y\sqrt{\frac{J}{J+1}}\delta_{JJ'}, & \check{L} &= \pm\frac{1}{2}\frac{\rho^2}{1 + \rho^2}\lambda_{JJ'},
\end{aligned} \tag{B3}$$

where the upper (lower) signs refer to β^- (β^+) decay. The coefficient $\lambda_{JJ'}$ is given in Eq. (A6) and

$$\bar{\Lambda}_{JJ'} \equiv \Lambda_{JJ'} \frac{\langle(\vec{J} \cdot \vec{j})^2\rangle - \frac{1}{3}J(J+1)}{J(2J-1)},$$

with $\Lambda_{JJ'}$ given in Eq. (A7).

REFERENCES

- Aad, G., *et al.* (ATLAS Collaboration), 2012, *Eur. Phys. J. C* **72**, 2241.
- Abele, H., 2008, *Prog. Part. Nucl. Phys.* **60**, 1.
- Ade, P. A. R., *et al.* (Planck Collaboration), 2014, *Astron. Astrophys.* **571**, A16.
- Adelberger, E. G., *et al.* (ISOLDE Collaboration), 1999, *Phys. Rev. Lett.* **83**, 1299.
- Altarev, I., *et al.*, 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 133.
- Altarev, I., *et al.*, 2012, *Nuovo Cimento* **C35**, 122.
- Altschul, B., 2013, *Phys. Rev. D* **88**, 076015.
- An, H., X. Ji, and F. Xu, 2010, *J. High Energy Phys.* **02**, 043.
- Ando, S.-i., J. A. McGovern, and T. Sato, 2009, *Phys. Lett. B* **677**, 109.
- Aseev, V. N., *et al.* (Troitsk Collaboration), 2011, *Phys. Rev. D* **84**, 112003.
- Aviv, O., *et al.*, 2012, *J. Phys. Conf. Ser.* **337**, 012020.
- Baessler, S., J. D. Bowman, S. Penttilä, and D. Počanić, 2014, *J. Phys. G* **41**, 114003.
- Baessler, S., *et al.*, 2008, *Eur. Phys. J. A* **38**, 17.
- Baker, C. A., *et al.*, 2006, *Phys. Rev. Lett.* **97**, 131801.
- Baker, C. A., *et al.*, 2011, *Phys. Procedia* **17**, 159.

- Ban, G., D. Durand, X. Fléchar, E. Liénard, and O. Naviliat-Cuncic, 2013, *Ann. Phys. (Amsterdam)* **525**, 576.
- Baron, J., *et al.* (ACME Collaboration), 2014, *Science* **343**, 269.
- Behr, J. A., and G. Gwinner, 2009, *J. Phys. G* **36**, 033101.
- Behr, J. A., *et al.*, 2014, *Hyperfine Interact.* **225**, 115.
- Beringer, J., *et al.* (Particle Data Group), 2012, *Phys. Rev. D* **86**, 010001.
- Bertolini, S., A. Maiezza, and F. Nesti, 2014, *Phys. Rev. D* **89**, 095028.
- Bhattacharya, T., V. Cirigliano, S. D. Cohen, A. Filipuzzi, M. González-Alonso, M. L. Graesser, R. Gupta, and H.-W. Lin, 2012, *Phys. Rev. D* **85**, 054512.
- Bhattacharya, T., S. D. Cohen, R. Gupta, A. Joseph, H.-W. Lin, and B. Yoon, 2014, *Phys. Rev. D* **89**, 094502.
- Bodek, K., *et al.*, 2011, *Phys. Procedia* **17**, 30.
- Bodek, K., *et al.*, 2014, *Proc. Sci.*, XLASNP 029.
- Bolokhov, P. A., S. Groot Nibbelink, and M. Pospelov, 2005, *Phys. Rev. D* **72**, 015013.
- Bolokhov, P. A., and M. Pospelov, 2008, *Phys. Rev. D* **77**, 025022.
- Bopp, P., D. Dubbers, L. Hornig, E. Klemt, J. Last, H. Schütze, S. J. Freedman, and O. Schärpf, 1986, *Phys. Rev. Lett.* **56**, 919.
- Braguta, V. V., A. A. Likhoded, and A. E. Chalov, 2002, *Phys. Rev. D* **65**, 054038.
- Branco, G. C., R. González Felipe, and F. R. Joaquim, 2012, *Rev. Mod. Phys.* **84**, 515.
- Broussard, L. J., *et al.*, 2014, *Phys. Rev. Lett.* **112**, 212301.
- Bsaisou, J., Ulf.-G. Meißner, A. Nogga, and A. Wirzba, 2015, *Ann. Phys. (Amsterdam)* **359**, 317.
- Bychkov, M., *et al.*, 2009, *Phys. Rev. Lett.* **103**, 051802.
- Byrne, J., P. G. Dawber, M. G. D. van der Grinten, C. G. Habeck, F. Shaikh, J. A. Spain, R. D. Scott, C. A. Baker, K. Green, and O. Zimmer, 2002, *J. Phys. G* **28**, 1325.
- Calaprice, F. P., S. J. Freedman, W. C. Mead, and H. C. Vantine, 1975, *Phys. Rev. Lett.* **35**, 1566.
- Callan, C. G., and S. B. Treiman, 1967, *Phys. Rev.* **162**, 1494.
- Campbell, B. A., and D. W. Maybury, 2005, *Nucl. Phys.* **B709**, 419.
- Carnoy, A. S., J. Deutsch, T. A. Girard, and R. Prieels, 1991, *Phys. Rev. C* **43**, 2825.
- Chatrchyan, S., *et al.* (CMS Collaboration), 2012, *J. High Energy Phys.* **08**, 023.
- Chatrchyan, S., *et al.* (CMS Collaboration), 2014, *J. High Energy Phys.* **05**, 108.
- Chupp, T. E., *et al.*, 2012, *Phys. Rev. C* **86**, 035505.
- Cirigliano, V., S. Gardner, and B. Holstein, 2013, *Prog. Part. Nucl. Phys.* **71**, 93.
- Cirigliano, V., M. González-Alonso, and M. L. Graesser, 2013, *J. High Energy Phys.* **02**, 046.
- Cirigliano, V., J. P. Jenkins, and M. González-Alonso, 2010, *Nucl. Phys.* **B830**, 95.
- Cirigliano, V., and I. Rosell, 2007, *J. High Energy Phys.* **10** 005.

- Colangelo, G., *et al.*, 2011, *Eur. Phys. J. C* **71**, 1695.
- Colladay, D., and V. A. Kostelecký, 1997, *Phys. Rev. D* **55**, 6760.
- Colladay, D., and V. A. Kostelecký, 1998, *Phys. Rev. D* **58**, 116002.
- Couratin, C., *et al.*, 2012, *Phys. Rev. Lett.* **108**, 243201.
- Curtis, R. B., and R. R. Lewis, 1957, *Phys. Rev.* **107**, 1381.
- Czarnecki, A., W. J. Marciano, and A. Sirlin, 2004, *Phys. Rev. D* **70**, 093006.
- Dekens, W., and D. Boer, 2014, *Nucl. Phys.* **B889**, 727.
- Dekens, W., and J. de Vries, 2013, *J. High Energy Phys.* **05**, 149.
- Dekens, W. G., and K. K. Vos, 2015, *arXiv:1502.04629*.
- de Vries, J., R. Higa, C.-P. Liu, E. Mereghetti, I. Stetcu, R. G. E. Timmermans, and U. van Kolck, 2011, *Phys. Rev. C* **84**, 065501.
- de Vries, J., E. Mereghetti, R. G. E. Timmermans, and U. van Kolck, 2011, *Phys. Rev. Lett.* **107**, 091804.
- de Vries, J., E. Mereghetti, R. G. E. Timmermans, and U. van Kolck, 2013, *Ann. Phys. (Amsterdam)* **338**, 50.
- de Vries, J., R. G. E. Timmermans, E. Mereghetti, and U. van Kolck, 2011, *Phys. Lett. B* **695**, 268.
- Díaz, J. S., 2014, *Adv. High Energy Phys.* **2014**, 305298.
- Díaz, J. S., V. A. Kostelecký, and R. Lehnert, 2013, *Phys. Rev. D* **88**, 071902.
- Dubbers, D., and M. G. Schmidt, 2011, *Rev. Mod. Phys.* **83**, 1111.
- Ebel, M. E., and G. Feldman, 1957, *Nucl. Phys.* **4**, 213.
- Erozolimskii, B., I. Kuznetsov, I. Stepanenko, I. Kuida, and Y. Mostovoi, 1991, *Phys. Lett. B* **263**, 33.
- Fléchar, X., P. Velten, E. Liénard, A. Méry, D. Rodríguez, G. Ban, D. Durand, F. Mauger, O. Naviliat-Cuncic, and J. C. Thomas, 2011, *J. Phys. G* **38**, 055101.
- Fléchar, X., *et al.*, 2008, *Phys. Rev. Lett.* **101**, 212504.
- Gardner, S., and D. He, 2012, *Phys. Rev. D* **86**, 016003.
- Gardner, S., and D. He, 2013, *Phys. Rev. D* **87**, 116012.
- Ginges, J. S. M., and V. V. Flambaum, 2004, *Phys. Rep.* **397**, 63.
- Glück, F., 1998, *Nucl. Phys.* **A628**, 493.
- González-Alonso, M., and J. M. Camalich, 2014, *Phys. Rev. Lett.* **112**, 042501.
- Gorelov, A., *et al.*, 2005, *Phys. Rev. Lett.* **94**, 142501.
- Green, J. R., J. W. Negele, A. V. Pochinsky, S. N. Syritsyn, M. Engelhardt, and S. Krieg, 2012, *Phys. Rev. D* **86**, 114509.
- Greenberg, O. W., 2002, *Phys. Rev. Lett.* **89**, 231602.
- Griffith, W. C., M. D. Swallows, T. H. Loftus, M. V. Romalis, B. R. Heckel, and E. N. Fortson, 2009, *Phys. Rev. Lett.* **102**, 101601.
- Groot Nibbelink, S., and M. Pospelov, 2005, *Phys. Rev. Lett.* **94**, 081601.
- Hallin, A. L., F. P. Calaprice, D. W. MacArthur, L. E. Piilonen, M. B. Schneider, and D. F. Schreiber, 1984, *Phys. Rev. Lett.* **52**, 337.
- Hardy, J. C., and I. S. Towner, 2005, *Phys. Rev. C* **71**, 055501.
- Hardy, J. C., and I. S. Towner, 2009, *Phys. Rev. C* **79**, 055502.
- Hardy, J. C., and I. S. Towner, 2014, *J. Phys. G* **41**, 114004.
- He, X.-G., and B. McKellar, 1993, *Phys. Rev. D* **47**, 4055.
- Herczeg, P., 1994, *Phys. Rev. D* **49**, 247.
- Herczeg, P., 1995, *Phys. Rev. D* **52**, 3949.
- Herczeg, P., 2001, *Prog. Part. Nucl. Phys.* **46**, 413.
- Herczeg, P., 2003, *Phys. Rev. D* **68**, 116004.
- Herczeg, P., 2005, *J. Res. Natl. Inst. Stand. Technol.* **110**, 453.
- Herczeg, P., and I. B. Khriplovich, 1997, *Phys. Rev. D* **56**, 80.
- Hinshaw, G., *et al.* (WMAP Collaboration), 2013, *Astrophys. J. Suppl. Ser.* **208**, 19.
- Holstein, B. R., 2014, *J. Phys. G* **41**, 110301.
- Huber, R., J. Lang, S. Navert, J. Sromicki, K. Bodek, S. Kistryn, J. Zejma, O. Naviliat-Cuncic, E. Stephan, and W. Haeberli, 2003, *Phys. Rev. Lett.* **90**, 202301.
- Hudson, J. J., D. M. Kara, I. J. Smallman, B. E. Sauer, M. R. Tarbutt, and E. A. Hinds, 2011, *Nature (London)* **473**, 493.
- Ibrahim, T., and P. Nath, 2008, *Rev. Mod. Phys.* **80**, 577.
- Ito, T. M., 2007, *J. Phys. Conf. Ser.* **69**, 012037.
- Ito, T. M., and G. Prezeau, 2005, *Phys. Rev. Lett.* **94**, 161802.
- Ivanov, A. N., M. Pitschmann, and N. I. Troitskaya, 2013, *Phys. Rev. D* **88**, 073002.
- Jackson, J. D., S. B. Treiman, and H. W. Wyld, 1957a, *Phys. Rev.* **106**, 517.
- Jackson, J. D., S. B. Treiman, and H. W. Wyld Jr., 1957b, *Nucl. Phys.* **4**, 206.
- Johnson, C. H., F. Pleasonton, and T. A. Carlson, 1963, *Phys. Rev.* **132**, 1149.
- Khachatryan, V., *et al.* (CMS Collaboration), 2014, *arXiv:1408.2745*.
- Khriplovich, I. B., 1991, *Nucl. Phys.* **B352**, 385.
- Khriplovich, I. B., and S. K. Lamoreaux, 1997, *CP violation without strangeness: Electric dipole moments of particles, atoms, and molecules* (Springer, Berlin/Heidelberg).
- Knecht, A., *et al.*, 2011, *Nucl. Instrum. Methods Phys. Res., Sect. A* **660**, 43.
- Knecht, A., *et al.*, 2012, *Phys. Rev. Lett.* **108**, 122502.
- Konrad, G., W. Heil, S. Baessler, D. Pocanic, and F. Gluck, 2010, *arXiv:1007.3027*.
- Konrad, G., *et al.* (Perc Collaboration), 2012, *J. Phys. Conf. Ser.* **340**, 012048.
- Kostelecký, V. A., and M. Mewes, 2004, *Phys. Rev. D* **69**, 016005.
- Kostelecký, V. A., and M. Mewes, 2009, *Phys. Rev. D* **80**, 015020.
- Kostelecký, V. A., and M. Mewes, 2012, *Phys. Rev. D* **85**, 096005.
- Kostelecký, V. A., and M. Mewes, 2013, *Phys. Rev. D* **88**, 096006.
- Kostelecký, V. A., and N. Russell, 2011, *Rev. Mod. Phys.* **83**, 11.
- Kostelecký, V. A., and S. Samuel, 1989, *Phys. Rev. D* **39**, 683.
- Kostelecký, V. A., and J. D. Tasson, 2009, *Phys. Rev. Lett.* **102**, 010402.
- Kozela, A., *et al.* (nTRV Collaboration), 2012, *Phys. Rev. C* **85**, 045501.
- Kraus, C., *et al.*, 2005, *Eur. Phys. J. C* **40**, 447.
- Lee, T. D., and C. N. Yang, 1956, *Phys. Rev.* **104**, 254.
- Li, G., *et al.*, 2013, *Phys. Rev. Lett.* **110**, 092502.
- Liaud, P., K. Schreckenbach, R. Kossakowski, H. Nastoll, A. Bussière, J. P. Guillaud, and L. Beck, 1997, *Nucl. Phys.* **A612**, 53.
- Liberati, S., 2013, *Classical Quantum Gravity* **30**, 133001.
- Liberati, S., and L. Maccione, 2009, *Annu. Rev. Nucl. Part. Sci.* **59**, 245.
- Liénard, E., 2014, in the 33rd Solvay Workshop on Beta-Decay Weak Interaction Studies in the Era of the LHC, Bruxelles, Belgium (private communication).
- Lindroos, M., and M. Mezzetto, 2010, *Annu. Rev. Nucl. Part. Sci.* **60**, 299.
- Maiezza, A., and M. Nemevšek, 2014, *Phys. Rev. D* **90**, 095002.
- Märkisch, B., H. Abele, D. Dubbers, F. Friedl, A. Kaplan, H. Mest, M. Schumann, T. Soldner, and D. Wilkin, 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 216.
- Mateu, V., and J. Portolés, 2007, *Eur. Phys. J. C* **52**, 325.
- Mattingly, D., 2005, *Living Rev. Relativity* **8**, 5.
- Mattingly, D., 2008, *arXiv:0802.1561*.
- Mendenhall, M. P., *et al.* (UCNA Collaboration), 2013, *Phys. Rev. C* **87**, 032501.
- Morita, M., and R. S. Morita, 1957, *Phys. Rev.* **107**, 1316.
- Moulson, M., 2013, *arXiv:1301.3046*.
- Müller, S., *et al.*, 2013, *Phys. Rev. D* **88**, 071901(R).
- Mumm, H. P., *et al.*, 2011, *Phys. Rev. Lett.* **107**, 102301.
- Mund, D., B. Märkisch, M. Deissenroth, J. Krempel, M. Schumann, H. Abele, A. Petoukhov, and T. Soldner, 2013, *Phys. Rev. Lett.* **110**, 172502.

- Naviliat-Cuncic, O., 2014, in the 33rd Solvay Workshop on Beta-Decay Weak Interaction Studies in the Era of the LHC, Bruxelles, Belgium (private communication).
- Naviliat-Cuncic, O., and M. González-Alonso, 2013, *Ann. Phys. (Amsterdam)* **525**, 600.
- Naviliat-Cuncic, O., and N. Severijns, 2009, *Phys. Rev. Lett.* **102**, 142302.
- Newman, R., and S. Wiesner, 1976, *Phys. Rev. D* **14**, 1.
- Ng, J., and S. Tulin, 2012, *Phys. Rev. D* **85**, 033001.
- Nico, J. S., 2009, *J. Phys. G* **36**, 104001.
- Noordmans, J. P., and K. K. Vos, 2014, *Phys. Rev. D* **89**, 101702(R).
- Noordmans, J. P., H. W. Wilschut, C. J. G. Onderwater, and R. G. E. Timmermans, 2015 (unpublished).
- Noordmans, J. P., H. W. Wilschut, and R. G. E. Timmermans, 2013a, *Phys. Rev. Lett.* **111**, 171601.
- Noordmans, J. P., H. W. Wilschut, and R. G. E. Timmermans, 2013b, *Phys. Rev. C* **87**, 055502.
- Olive, K. A., *et al.* (Particle Data Group), 2014, *Chin. Phys. C* **38**, 090001.
- Otten, E. W., and C. Weinheimer, 2008, *Rep. Prog. Phys.* **71**, 086201.
- Pattie, R. W., K. P. Hickerson, and A. R. Young, 2013, *Phys. Rev. C* **88**, 048501.
- Počanić, D., *et al.* (Nab Collaboration), 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 211.
- Pospelov, M., and A. Ritz, 2005, *Ann. Phys. (Amsterdam)* **318**, 119.
- Prezeau, G., and A. Kurylov, 2005, *Phys. Rev. Lett.* **95**, 101802.
- Regan, B. C., E. D. Commins, C. J. Schmidt, and D. DeMille, 2002, *Phys. Rev. Lett.* **88**, 071805.
- Sakharov, A. D., 1967, *JETP Lett.* **5**, 24 [http://www.jetpletters.ac.ru/ps/1643/article_25089.shtml].
- Schumann, M., T. Soldner, M. Deissenroth, F. Glück, J. Krempel, M. Kreuz, B. Märkisch, D. Mund, A. Petoukhov, and H. Abele, 2007, *Phys. Rev. Lett.* **99**, 191803.
- Seng, C.-Y., J. de Vries, E. Mereghetti, H. H. Patel, and M. Ramsey-Musolf, 2014, *Phys. Lett. B* **736**, 147.
- Serebrov, A. P., *et al.*, 1998, *J. Exp. Theor. Phys.* **86**, 1074.
- Serebrov, A. P., *et al.*, 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 276.
- Severijns, N., 2014, *J. Phys. G* **41**, 114006.
- Severijns, N., M. Beck, and O. Naviliat-Cuncic, 2006, *Rev. Mod. Phys.* **78**, 991.
- Severijns, N., and O. Naviliat-Cuncic, 2011, *Annu. Rev. Nucl. Part. Sci.* **61**, 23.
- Severijns, N., M. Tandecki, T. Phalet, and I. S. Towner, 2008, *Phys. Rev. C* **78**, 055501.
- Shidling, P. D., *et al.*, 2014, *Phys. Rev. C* **90**, 032501.
- Sprouse, G. D., and L. A. Orozco, 1997, *Annu. Rev. Nucl. Part. Sci.* **47**, 429.
- Sytema, A., *et al.*, 2015 (unpublished).
- Totsuka, Y., *et al.*, 2014, *Phys. Part. Nucl.* **45**, 244.
- Towner, I. S., and J. C. Hardy, 2010, *Rep. Prog. Phys.* **73**, 046301.
- Triambak, S., *et al.*, 2012, *Phys. Rev. Lett.* **109**, 042301.
- Ullman, J. D., 1978, *Phys. Rev. D* **17**, 1750.
- van der Grinten, M. G. D., *et al.* (CryoEDM Collaboration), 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 129.
- Vetter, P. A., J. R. Abo-Shaeer, S. J. Freedman, and R. Maruyama, 2008, *Phys. Rev. C* **77**, 035502.
- Vos, K. K., J. P. Noordmans, H. W. Wilschut, and R. G. E. Timmermans, 2014, *Phys. Lett. B* **729**, 112.
- Vos, K. K., H. W. Wilschut, and R. G. E. Timmermans, 2015a (unpublished).
- Vos, K. K., H. W. Wilschut, and R. G. E. Timmermans, 2015b, *Phys. Rev. C* **91**, 038501.
- Wang, P., 2007, “Neutrino mass implications for physics beyond the standard model,” Ph.D. thesis (Caltech).
- Wauters, F., A. García, and R. Hong, 2014, *Phys. Rev. C* **89**, 025501.
- Wauters, F., *et al.*, 2010, *Phys. Rev. C* **82**, 055502.
- Webber, D. M., *et al.* (MuLan Collaboration), 2011, *Phys. Rev. Lett.* **106**, 041803.
- Weinberg, S., 1958, *Phys. Rev.* **112**, 1375.
- Weinberg, S., 1979, *Phys. Rev. Lett.* **43**, 1566.
- Wichers, V. A., T. R. Hageman, J. van Klinken, H. W. Wilschut, and D. Atkinson, 1987, *Phys. Rev. Lett.* **58**, 1821.
- Wietfeldt, F. E., and G. L. Greene, 2011, *Rev. Mod. Phys.* **83**, 1173.
- Wietfeldt, F. E., *et al.*, 2009, *Nucl. Instrum. Methods Phys. Res., Sect. A* **611**, 207.
- Wilschut, H. W., *et al.*, 2013, *Ann. Phys. (Berlin)* **525**, 653.
- Yerozolimsky, B., I. Kuznetsov, Y. Mostovoy, and I. Stepanenko, 1997, *Phys. Lett. B* **412**, 240.
- Young, A., W. Anderson, F. Calaprice, G. Cates, G. Jones, D. Krieger, and R. Vogelaar, 1995, *Phys. Rev. C* **52**, R464.